European Commission

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Human appropriation of net primary production of Sahel ecosystems under a changing climate to 2050

Food security and resource-use balance in the Sahel

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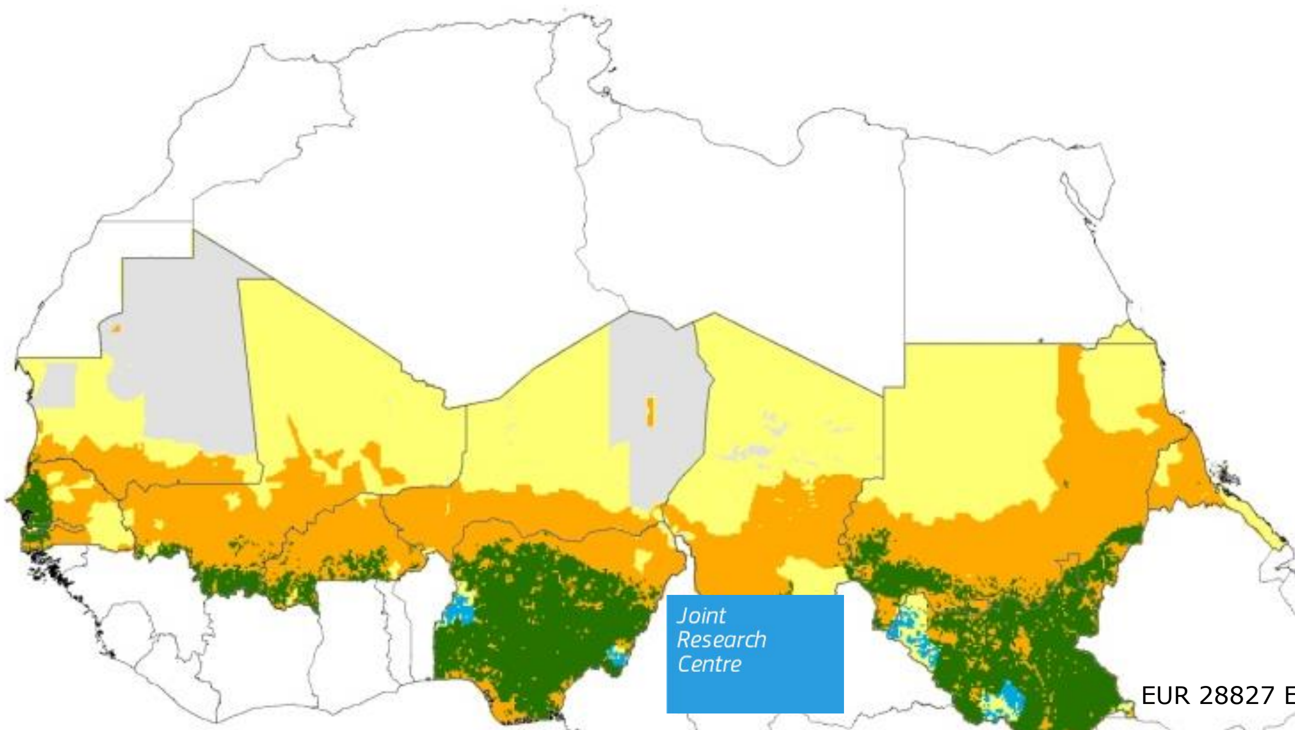
2019



Own elaboration

Joint Research Centre

EUR 28827 EN

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JRC Science Hub
https://ec.europa.eu/jrc

JRC108643

EUR 28827 EN

PDF ISBN 978-92-79-74274-3 ISSN 1831-9424 doi:10.2760/500533

Luxembourg: Publications Office of the European Union, 2019

How to cite: Ceccarelli, T., Winograd, W., Garzon Delvaux, P.A., Hoek, S. and Gomez y Paloma, S., Human appropriation of net primary production of Sahel ecosystems under a changing climate to 2050: Food security and resource-use balance in the Sahel, EUR 28827 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-79-74274-3, doi:10.2760/500533, JRC108643.

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Acknowledgements

We would like to thank the team of Wageningen University & Research (Alterra) for its dedication in setting the basis for the analysis. Also, our thanks go to Pierre Fabre and Roberto Aparicio, DG EC DEVCO C1 unit officers, for comments on previous versions of this report. This work was partially funded by the project "Technical and scientific support to agriculture and food and nutrition security sectors (TS4FNS)" within the Administrative Arrangement between DG International Cooperation and Development (DEVCO) and DG Joint Research Centre (JRC) via the AREA Framework Contract 154591-2015 A08-NL.

Abstract

Responding to the food security challenge in the Sahel mainly relies on the supply of goods and services from ecosystems of the region. The evolution of the Sahelian population in the wake of climate change questions whether available biomass from agriculture and natural vegetation will be covering future human needs. To explore this issue, we present a prospective study of the human carrying capacity of Sahel ecosystems balancing its biomass supply and demand to the year 2050. This was obtained by applying a net primary production (NPP) demand and supply model based on satellite derived NPP, the most reliable information on land cover, crop types and Land Utilisation Types (LUTs), as well as official production (completed by net trade flows) statistics from FAOSTAT and UN population projections. How four alternative agriculture scenarios affect the Sahel's carrying capacity, given its variability and expected vulnerability to climate change (CC), is also addressed contrasting possible futures. Results, expressed in terms of the human appropriation of NPP (HANPP), and supported by scenario narratives, show that HANPP evolves from the current 29% (food, feed and fuel components included) to 75%-88% depending on the scenario. The approach also generated HANPP maps indicating areas of special concern ("hot spots") as well as those expected to generate opportunities ("hope spots") in terms of local NPP supply and demand balance. The two scenarios with most agricultural technological improvements achieve the most favourable NPP food share results but fall short of compensating for a more than doubling demand over the same period. Today about 15% of food biomass is imported against an expected 40% by the year 2050 and up to 65% in the least favourable scenario of this prospective. These are conservative estimates as they do not account for the likely future change in individual dietary preferences and increases in consumption. Such projections point to the need to reinforce agriculture policy with complementary assertive strategies through the diversification of the economy and adapted regional trade policy.

1 Introduction

1.1 Background

Africa, which still regularly suffers from food emergencies, is to experience a doubling of its population to about 2,13 billion individuals by the year 2050 (United Nations 2015) pointing to a "great balancing act" between the increasing and diversifying needs and the resources available in terms of land, agricultural inputs and wild resources such as fisheries and common land (Searchinger, Hanson et al. 2014). Although human management can foster the production of biomass (e.g. agriculture) for food, fibre and fuel, land capability to produce such biomass remains a key limiting factor in reaching or falling short of the sought-after balance (Running 2012). African agriculture productivity has unequally risen since the 1990s, averaging a 3.2% annual growth (1990-2011) – just above demographic growth (Wiggins 2014) although half that of the 2003 Maputo Objectives (CAADP 2003). Remaining land availability provides opportunities but historical and current resource use patterns in Africa are associated with the degradation of 65% of arable land, 30% of grazing land and 20% of forests (FAO 2008), partially jeopardizing existing assets to respond to the challenge. Moreover, most additional available land is made of fragile soils with characteristics requiring adequate management (Jones, Breuning-Madsen et al. 2013).

However, evidence rejects reducing hunger to the decline in food availability such as Sen's (1981) analysis looking at the lack of access and entitlement to food. Hunger remains not only because of a production gap but because of conflict, lack of job opportunities and social protection; and access to land (FAO, IFAD et al. 2014). It is also the result of the unsustainable natural resource use, on which the rural poor are directly dependent for their livelihood (Cavendish 2000; Kamanga, Vedeld et al. 2009; Wunder, Angelsen et al. 2014).

In addition to these conventional challenges to food security, there are emerging ones such as the effect of climate change on agriculture output (Niang, Ruppel et al. 2014; Porter, Xie et al. 2014) and its related health implications (Springmann, Mason-D'Croz et al. 2016).

Parts of Africa and, the Sahel in particular, have already demonstrated to be vulnerable to climate variability shocks even if not unused to droughts (Masih, Maskey et al. 2014). In the Sahel, the end of the 20th century droughts (late1960s-mid.1980s) meant a 20-40% decline in rainfall and a 1.3°C temperature increase) (Hulme 2001; Masih, Maskey et al. 2014) with their associated disruptive effects on its mainly rainfed agriculture (FAO Aquastat and land, year 2011) and more broadly on societies (Sen 1981; Batterbury and Warren 2001). That said, signs of a “re-greening” of the region over the last 30 years also point to a certain resilience of its ecosystems to such events (Herrmann, Anyamba et al. 2005; Dardel, Kergoat et al. 2014). However, the Sahel has experienced new major droughts (2010, 2012) which have partially been linked to recent food crises (OCHA 2014). However, the persistence of such crises is mainly attributed to social factors (Epule, Peng et al. 2014).

One way of looking at the balance between food needs and resources is that of estimating the human appropriation of Sahelian land (and associated ecosystems) capacity to produce biomass. Along with other sustainability indicators, such as the Ecological Footprint (EF), Human appropriation of net primary production (HANPP) is an indicator of reference for the Convention on Biological Diversity (CBD) to monitor sustainable consumption within the Aichi targets (SCBD 2012)[1]. The produced biomass can be quantified as the Net Primary Production (NPP) which computes the net carbon captured by land vegetation in a given period and area (Haberl, Wackernagel et al. 2004). In turn, the HANPP quantifies the existing balance between biomass net-production (i.e. NPP) and net-consumption by society.

[1] The Strategic Plan for Biodiversity 2011-2020 of the CBD contemplates a set of 20 targets, collectively known as the Aichi targets and include, inter-alia, Sustainable production and consumption (target N5).

HANPP comprises total biomass extractions and changes along forgone productivity due to land use changes (Haberl, Erb et al. 2007; Krausmann, Erb et al. 2013).

1.2 Objectives

The report aims at exploring the human appropriation of net primary production (HANPP) of the Sahel in the context of global changes; namely population growth and climate change to the year 2050. This projection unfolds around the variations of the projected results according to different agriculture development scenarios within the global changes context.

The report first presents an overview of a literature review covering both methodological and empirical precedents in analysing carrying capacity of the region and the resource-use balance of Sub-Sahara Africa (SSA) in general. Then, the methods and data used for the projections are presented followed by the results encompassing 11 countries of the Sahel (Burkina Faso, Chad, Eritrea, Gambia, Mali, Mauritania, Niger, Nigeria, Senegal, Soudan and South Sudan) and accompanied by scenario narratives.

2 Literature Review

2.1 Approach

The main goal of this review is to provide an account of the existing literature on two topics:

1) State of the art of methodologies for estimating (human) carrying capacity in developing contexts;
2) Key trends for SSA and in particular for the Sahel.

In this context, the literature review was carried out based on the consultation of academic journal articles, books, reports, reviews, web/internet sites and "grey literature". The time period for the review was originally 2010-2015. Nevertheless, given the fact that important studies related to issues which are relevant to our review have been conducted between 1990 and 2010, the review was extended to a broader time period. Indeed, during the 80s and 90s a series of programs were developed for the Sahel/SSA region related to desertification, climate variability/change and food security issues, producing a wealth of reports and information. Emphasis was given to agriculture which is the main domain of interest of the present study.

References were further grouped and prioritized, based on their relevance and usefulness. Key references were analyzed in more details. A number of findings were finally derived, which are relevant to the topics at stake as well as to establish a link with the definition of the scenarios in terms of narratives, key drivers, and elements of the same scenarios. Other contextual information derived from this review will be part of the documentation in support to the scenario building and modelling. Implications for and added value of this study are also discussed, followed by a commented list of the references.

Given the geo-political, institutional and research context of the review, the main languages used in the search for relevant publications were English and French. However, French speaking research and development communities are increasingly publishing more of their work in English or in both French and English. For instance the AGRIMONDE programme, developed by the Institut national de la recherche agronomique (INRA) and the Centre de coopération internationale en recherche agronomique pour le développement (CIRAD) have bilingual publications.[2]

[2] See for instance Paillard, S., S. Treyer, et al. (2014). Agrimonde–Scenarios and Challenges for Feeding the World in 2050. Versailles, Editions Quæ, Springer Science & Business Media.

AGROPOLIS international also allows choosing the preferred language (http://www.agropolis.fr/publications/dossiers-thematiques-agropolis.php).

The academic literature search was carried out mainly using the Wageningen UR Digital Library (http://www.wageningenur.nl/en/Expertise-Services/Facilities/Library.htm).

In order to cover most French research institutions and programs, a search was carried out using the IRD publication internet facility including the African regional documentation centers (http://horizon.documentation.ird.fr/) and the French Mixed Research Units publication (including IRD, CIRAD, CEMAGREF, ENGREF, at https://en.ird.fr/the-research/research-units-list). Also a search on Cairn (http://www.cairn.info/), an internet portal accessing also the National Library of France, was conducted on selected keywords.

The search resulted in a number of relevant publications (peer reviewed articles and book chapters) published between 1990 and 2015 although, as anticipated, earlier references were also reviewed as needed.

The main institutional internet sites consulted are listed in the table below:[3]

Table 1 List of institutional Web sites and URL

Institution	**Web sites URL**
AGROPLIS international	http://www.agropolis.fr/changement-climatique/liste-exemples-recherche.php
CILSS	http://www.cilss.bf/
Club du Sahel et de l'Afrique de l'Ouest	http://www.oecd.org/swac/
Observatoire du Sahara et du Sahel	http://www.oss-online.org/
AGRHYMET	http://www.agrhymet.ne/
ECOWAS	http://www.ecowas.int/
CEDEAO	http://www.ecowas.int/?lang=fr
Institut du Sahel	http://www.insah.org/
FAO, Regional Office for Africa	http://www.fao.org/africa/resources/publications/en/
CCAFS West Africa	https://ccafs.cgiar.org/regions/west-africa
IWMI Africa	http://westafrica.iwmi.cgiar.org/publications/
CSI CGIAR consortium	http://www.cgiar-csi.org/

[3] Covering reports, reviews, policy documents, plans and strategies, project reports and evaluation reports, case study analyses, position papers, websites and other "grey literature".

IRD documentation center	http://horizon.documentation.ird.fr/
CIRAD publication	http://www.cirad.fr/en/publications-resources
French common research unit publications	https://en.ird.fr/the-research/research-units-list

Source: Own elaboration

The main terms used for the specific searches included: "SSA and Sahel", "carrying capacity", "NPP and Human appropriation of NPP", "ecological footprint", "food security and early warning", "scenarios for Africa", "climate change and climate variability", "development contexts and scenarios", "agriculture production", "land use and land use change", "driving factors and driving forces", "adaptation and vulnerability", "migration and population", "poverty", "land tenure and land grabbing", "land degradation and desertification", "economic growth and agriculture", "land resources and land tenure", "livestock", "rainfed farming and crops". "agriculture and landscape policies", "agriculture scenarios and inputs", "farming production systems and yield gaps", "smallholders and production systems", "scenarios and pathways".

The French terms used in the search included: "Sahel et Afrique de l'ouest"; "Capacité de charge"; "Productivité primaire nette et Appropriation humaine de la Production primaire nette"; "Empreinte écologique"; "Sécurité alimentaire et l'alerte précoce" ; "Scenarios pour l'Afrique" ; "changement et variabilité climatique" ; "Contexte et scénarios de développement", "Productivité agricole"; "Changements et utilisation des terres", "Forces motrices"; "Adaptation et vulnérabilité" ; "Migrations et population", "Pauvreté", "Régime foncier" ; "Dégradation des terres et désertification" ; "Croissance économique et agriculture"; "Élevage" ; "Agriculture et cultures pluviales"; "Scénarios agricoles et intrants", "Systèmes de production agricole et écarts de rendements", "Petits exploitants et systèmes de production".

As mentioned the references found were first grouped according to the two topics in the literature review and further based on relevant themes. Regarding methodologies, two main themes were identified, i.e. basic studies on concepts and methods and applied studies for SSA and the Sahel. For the part on trends in SSA and the Sahel, a first theme relates to NPP, HANPP and carrying capacity trends, while a second one encompasses more general trends in land use, agriculture and vulnerability. References were then classified and assessed in respect to their usefulness for the present study. Other references less directly related complete the gathered material.

In the next section, the key findings from the literature review are discussed and remarks are made, namely on the implications and areas where the present work is expected to bring added value in respect to the existing studies. The discussion section is summarized by two tables intended to ease the comparison between the most relevant studies. Elements in the tables include metrics and indicators (e.g. NPP, HNPP, carrying capacity, ecological footprint), time horizon and trends (past, present, future) analysed, spatial coverage and detail, modelling approach and main data sources used and finally, key outcomes of the trends identified for SSA and the Sahel.

2.2 The state of the art in approaching carrying capacity

2.2.1 Carrying capacity: definitions and main approaches

Carrying capacity may be defined as "the optimal level of production that guarantees equilibrium between the renewability of a certain resource limiting a given type of land-use and the level of its exploitation" (Kessler 1994). It is possible to distinguish three approches to estimate and assess carrying capacity (Wackernagel and Rees 1996; Lane 2010):

- Societal parameters, which are largely extensions of demographic or economic models and are generally limited in their scope (i.e. mostly demographically based rather than resource-driven ignoring or downplaying the finite nature of the physical environment and possible environmental impacts);
- Environmental constraints to resource consumption and/or environmental impacts to determine population limits. The most common examples are based on the Ecological Footprint approach;
- System-based carrying capacity methodologies that not only examine a number of concurrent factors effecting population limits but also consider the relationships between these factors.

Most of the studies assessed belong to the second and third type of methodologies in that they consider both demand (resource base) and supply (demography and consumption patterns), taking into account concurrency or even relationships between factors.

The Ecological Footprint (EF) is a measure of the demand human activities place on the biosphere. It measures the amount of biologically productive land (as well as the water area) required to produce all the resources an individual, population, or activity consumes, and to absorb the waste these generate, with the prevailing technological solutions and resource management practices. Land is converted into a normalized measure called "global hectare", assuming world average productivity. This makes it possible to compare the footprint with the amount of productive area available to generate these resources and to absorb the waste, which is indicated as biological capacity (bio capacity) and is also calculated based on world average productivity. When human demand exceeds available bio capacity, this results in the depletion of the standing stocks of an ecosystem. EF analysis is now widely used as an indicator of environmental sustainability, given its ability to encompass a vast amount of information in a single quantitative measure and to attempt to operationalize the concepts of carrying capacity and sustainability. However, EF analysis still has a number of serious shortcomings related to assumptions, methods, and data (Van den Bergh and Verbruggen 1999). In response, a "Footprint 2.0" was later developed offering a series of theoretical and methodological improvements to the standard footprint approach (Venetoulis and Talberth 2008).

An alternative is the use of Net Primary Production (NPP) instead of the "global hectare" as the basis for the normalization.[4] It has been suggested that human appropriation of NPP (HANPP) is a more explicit measure of the intensity of human pressure on ecosystem use than the ecological footprint. This is related to the fact that EF focuses more on demand than on supply (UNEP 2005). Moreover NPP shifts the basis of bio capacity estimates from the sole agricultural potential to all biomass production. Finally NPP provides a basis for real time mapping of bio capacity through satellite based measurements (Abdi, Seaquist et al. 2014).

[4] NPP can be defined as the total amount of energy that is fixed biologically after subtracting the respiration of primary producers. It is a measure of the resources available for the maintenance, growth, and reproduction of all consumers and decomposers on the planet.

Apart from the cited advancements in the EF, NPP is nowadays frequently utilized as the numerary for different approaches to demand and supply estimates. As shown in this literature review NPP and HANPP are often used as proxy indicators for carrying capacity. Nevertheless main findings from research point to the fact that HANPP alone cannot, as sometimes suggested, be used as a measure of carrying capacity (Krausmann, Erb et al. 2013). In fact, analyses of long-term NPP and HANPP trajectories in combination with accounts of material and energy flows can provide important insights into the factors affecting population limits as well as their relationships as indicated in the first type of approaches listed above.

At the same time carrying capacity and HANPP need to be used carefully when assessing ecological limits to growth and sustainability, because (a) economic growth may proceed even without growing biomass use, (b) long-term studies have shown that HANPP may decline during an industrialization phase if biomass harvest grows due to agricultural intensification rather than to an extension of farmed areas (Krausmann, Erb et al. 2013), (c) carrying capacity is determined by ecosystem thresholds related with specific exploitation levels and technologies within a specified spatial-temporal scale, and not only based on simple quantitative parameters such as the area of land under a given use (Kessler 1994).

To conclude several workable examples of carrying capacity assessments have emerged suggesting that it is possible to create a model that, while not definitive, provides valuable insight into such complex systems (Lane 2010). Remaining challenges include: the integration of whole-systems into the models, the consideration of cultural habits (such as food preferences), the adoption of dynamic timeframes (allowing for interactions, feedbacks, projections), the account of a wide range of key natural and social constraints, the ability to suggest alternatives and detect contradictory conditions, the use of fine-grained and credible data, and the interaction with actors. It is believed that HANPP, in combination with scenario development and narratives, can effectively support the carrying capacity assessment and its analysis in this perspective.

The next paragraphs analyze in more details the outcomes of the literature review from different perspectives.

2.2.2 Time horizon and trends analysed

As depicted in Table 2, perspective scenarios are limited to Ardö (2015) while most studies adopting the NPP approach analyze only past and actual conditions. Other studies are investigating future scenarios but apply different approaches (Blein, Soulé et al. 2008; WWF and AFDB 2012; Jalloh, Nelson et al. 2013).

2.2.3 Spatial coverage and detail

Studies which are specifically targeting SSA and the Sahel are limited to Abdi et al. (2014) and to Ardö (2015). Jalloh et al. (2013) and Blein et al.(2008) extend their analysis to ECOWAS Countries. Other studies are conducted at macro-regional, continental or global scale.

Some of the studies analyzed have a sufficient spatial detail and can be regarded as truly spatially explicit. For instance the studies conducted by Abdi et al. (2014) and Ardö (2015) based on remote sensing estimates of NPP, generated gridded outcomes with 1 km resolution. Fetzel et al. (2012) report their results at 10 km resolution and Jalloh et al. (2013) at 15-arc-minute (around 28 km at the equator) resolution. The remaining studies however (Blein, Soulé et al. 2008; WWF and AFDB 2012) report at country or regional levels.

2.2.4 Integrating agriculture in the scenarios

The integration of agriculture (and namely of detailed information on crops and related farm management) is not done in most of the studies scrutinized, where agriculture is taken into account, at most, in the scenario narratives. An exception is in Blein et al. (2008), where four developed scenarios [5] are related to detailed assumptions in the agricultural sector. Scenario elements include growth in cultivated areas, improved yields, increased animal production, and growth in surface areas under water management. However, the outcomes of this study are reported only at regional and country levels.

2.2.5 Scenario drivers and narratives

The literature review shows that often the existing studies are based on a small set of drivers (e.g. GDP and population growth). This not only holds in terms of the modelling but also for the same scenario narratives used to support the NPP and carrying capacity assessments. As a result, in many studies the dynamics, pathways and transitions are directly derived from this limited set of drivers (e.g. increase in population means increase in land conversion) as in Ardö (2015). In reality, the dynamics of change are more complex and interconnected with other drivers such as, for instance, land use potential, gap in technology adoption, importance of trade patterns and possible land use change as a consequence of the expansion of bioenergy (Blein, Soulé et al. 2008; WWF and AFDB 2012; Jalloh, Nelson et al. 2013; Africa Progress Panel 2014; Lambin, D'haen et al. 2014).

The goal of the narratives for agriculture scenarios is to avoid oversimplification in the scenario assumptions: i.e. drivers are connected between them and coherent with other scenarios elements. In fact each driver and scenario element could be related and connected with other drivers and scenarios elements that reflect the real nature of the dynamics and interconnected pathways and transitions. Narratives would ease the identification and the assessment/analysis of the main feedbacks and dynamics between and within scenarios (e.g. trajectories, synergies, thresholds, tipping points, land use/cover changes).

2.2.6 Source of data for NPP demand and supply estimates

Most of the studies assessed in the present review (with special reference to SSA and the Sahel) are based on specific supply and demand datasets.

Notwithstanding known limitations of national production official statistics of the countries (crops, livestock, wood, burned biomass for land clearing) are used as a proxy of NPP demand. FAOSTAT data are generally utilized as the source (see for instance Abdi et al., 2014). In some studies more generic assumptions are made as far as the demand side is concerned, using per-capita values which are then multiplied by population estimates (Ardö 2015). Satellite derived estimates are regarded as the most objective way of assessing NPP supply (Abdi, Seaquist et al. 2014), despite shortcomings related to reported overestimation/underestimation of MODIS based NPP in specific Sahelian conditions (Mu, Zhao et al. 2007).

2.3 Consumption of land-based resource in the Sahel: Existing data and projections

Looking at the recent past and present of the general balance of land-based resources produced and what is captured by society over 22 countries in sub-Saharan Africa, Abdi et al. (2014) concluded that, for the time horizon 2000-2010, the NPP supply had been near-constant (with an inter-annual variability of approximately 1.7%). However, NPP demand increased from 19% to 41% of the supply. On the demand side, the largest increase was for food (20.4%) followed by feed (16.7%) and fuel (5.5%). Large areas, most notably of West

[5] 1. Current trend (agricultural growth through the expansion of farmland), 2. Breakaway Scenario (Agricultural growth through massive transformation of agriculture), 3. Moderate Scenario 1 (Agricultural growth through partial transformation of agriculture), and 4. Moderate Scenario 2 (Regional crisis in a favourable international context).

Africa as well as of Ethiopia and Somalia experienced a NPP demand that is much larger (> 200%) than the available supply.

In a similar vein, Fetzel et al. (2016) estimated that HANPP in Africa had increased by 55% from 1980 to 2005 (85% for West Africa). Evaluations are based on global estimates of actual NPP after Haberl et al. (2007) and Erb et al. (2009);both derived from FAOSTAT statistics. The approach also accounts for what is initially extracted by humans but eventually backflows into nature. Over the period, the per capita HANPP (NPP extracted by each individual) decreased for Senegal, Chad and Nigeria. Moreover, the ratio of used biomass to total HANPP (including land-use change) in Africa 35% and significantly lower than the world average (48%), indicating that most of the additional NPP resulted from the expansion of the agricultural frontier in turn suggesting the potential for improving efficiency in biomass production (e.g. intensification of agriculture). Associated studies (Fetzel, Niedertscheider et al. 2012) looking at aggregated/country-level data have also defined an 'embodied' HANPP (eHANPP) as a country/regional level enhancement of the HANPP analysis which also accounts for net trade flows of biomass between regions and countries. In this analysis, sub-Saharan African countries appear to be net producers of biomass, whereas North African ones are net importers.

Perspective scenarios studies for the Sahel are limited. Ardö (2015) uses NPP supply estimates as in Abdi et al. (2014) (calculated as average over the period 2000-2010). A 15 % reduction is then applied as a simulated effect of a severe drought hypothesized for the year 2030. On the demand side, a mean annual consumption of 2 t NPP per capita is assumed (Imhoff, Bounoua et al. 2004). Average per-capita consumption values are then multiplied by gridded population densities to obtain spatially explicit per-capita consumptions. These are further projected to the year 2030 using two population growth scenarios (assuming low and high fertility rates). Two scenarios are developed: an 'optimistic' one assuming mean ('historical', i.e. 2000-2010) NPP and low fertility rates, and a 'pessimistic' one assuming reduced NPP (- 15%) and high fertility rates. Vulnerability classes are finally derived, with the class 'very vulnerable' occurring with NPP per capita values of <1.25 MgC, and the class 'vulnerable' with values of < 2.5 MgC. Only aggregated results are presented in the study apart from those reported in the form of maps (see below). These indicate that in case the low (high) fertility rate scenario is assumed, the rural population living in very vulnerable areas in year 2030 will be 150 (170) million while 68 (80) million will be living in vulnerable areas. The spatial distribution is shown in Figure 1. Areas in red are assumed to be very vulnerable and areas in pink to be vulnerable. The population in the Sahelian area is clearly indicated as being more at risk in both scenarios. Also parts of Nigeria and Ethiopia outside the Sahel are regarded as very vulnerable in both scenarios.

Other studies investigated both past and future trends but applied different approaches to HANPP. Blein et al. (2008) for instance, analysed agricultural supply and demand trends for the ECOWAS countries over the period 1980-2030. Demand and regional production forecasts were generated and used as input in four scenarios of agricultural growth projected to the year 2030. The main conclusion of the study is that the region is altogether improving its production capacities and has the necessary resources to achieve food security over the next 25 years. However it is the humid and semi-humid part of the study area which is playing a decisive role in the regional context. In the framework of the joint CIRAD and INRA Agrimonde project, Paillard et al. (2014) analysed the balance of food biomass resources and their use for the world divided in regions, including SSA, to the year 2050. The resource balance is completed by comparing the projected production and consumption in calories equivalent from land-based sources (plant and animal). Using the AGROBIOM model and two scenarios developing future macro trends, including different assumptions about diet trends, the analysis concluded that the world as a whole could feed itself by 2050. However SSA would be experiencing a deficit ranging from 5% to 50% of all the calories needed in the less optimistic scenario depending on the evolution of diets and the reduction of waste. Jalloh et al. (2013) analysed the impact of climate changes on agricultural production over the whole of West Africa (ECOWAS countries plus Mauritania) for the period 2000-2050. They used a crop model (DSSAT) and MapSPAM crop areas to estimate crop production under different climate change scenarios. The outcomes are then used in a Partial Equilibrium Agricultural Model (IMPACT) for deriving agricultural vulnerability scenarios (crop-specific). Indicators are: production, yield, area, net exports, and world prices. Human vulnerability scenarios are finally derived simulating the impact of future GDP and population growth in terms of malnutrition rates and kilocalories per capita. As to the trends observed by 2050 in crop production, the results of the analysis conducted at country level clearly show an increase in the case of maize, millet, and sorghum. The area under cultivation of both millet and sorghum increases, while the area under cultivation of maize is expected to decrease. The productivity of all three crops is assumed to increase (due to increased use of inputs under improved management practices and the availability of improved varieties) although still far from potential yield levels. As a matter of example, changes for sorghum in terms of areas, yield and overall production are reported. In turn, van Ittersum et al. (2016) looked at whether SSA could be self-sufficient in 5 key cereals by 2050. Analysing 10 countries of the region it estimated cereal demand (caloric content/maize equivalent) with the projected population increase and per capita consumption. Individual consumption is assumed to depend on income growth resulting in additional cereal demand for use as livestock feed and other purposes and was estimated using a partial equilibrium model for the agricultural sector (IMPACT). Cereal production capacity was estimated on existing crop land through various degrees of yield gap closure and other strategic options (e.g., expanded irrigation area, increased cropping intensity, and crop area expansion). They concluded that SSA already imports about 20% of its five main cereal needs. Closing the existing yield gap alone on existing cropland area (from 20% to 50% or even to an optimistic 80%) is not expected to be enough to respond to future population growth to the year 2050. Both complex and uncertain additional agriculture developments such as intensification and full realization of irrigation potential are also needed to avoid a massive cropland expansion with associated environmental impact or vast import dependency, or both.

In their African Ecological Footprint Report, the WWF and the African Development Bank (AFDB) (2012) investigated the ecological footprint for the entire continent at country level, based on previous global estimates from the Global Footprint Network[6] (GFN). This is a retrospective study (1961-2008) where the Ecological Footprint is compared with bio capacity. The outcomes of this study indicate that Africa's bio capacity increased by 30% over the last 40 years, mainly as a result of increased agricultural production. Nevertheless, these production gains have not kept pace with the increasing population growth and demand. Available per capita bio capacity has declined to just 37 % of its 1961 value. However values improved or remained stable for Sahelian Countries like Mauritania, Mali, Burkina, and Chad.

When looking at the geographical patterns, although aggregated at country level and for broad agro-ecological zones as in this study, it becomes evident that humid and semi-humid areas are playing a decisive role in the regional agricultural dynamics. The region is altogether improving its production capacities and has the necessary resources to achieve food security over the next 25 years.

2.4 Summary tables comparing selected studies from the literature review

[6] http://www.footprintnetwork.org

Table 2 highlights the main features of selected studies following the NPP and HANPP approach, with a focus on SSA and the Sahel.

Table 3 summarizes the same features of studies having a broader focus on agriculture scenarios. In this case metrics are different than NPP and HANPP: ecological footprint, carrying capacity, food vulnerability indicators, etc. The above information will be useful for the scenarios narratives as well as for the modeling part of this study.

Table 2 Key studies using the NPP and HANPP approaches (SSA and the Sahel)

Key study	Metrics and Indicators	Trends			Time horizon	Spatial detail	Spatial Coverage	Modelling approach and main data sources	Key trends for SSA and the Sahel
		Past	Actual	Future					
Abdi et al., 2014	**NPP** supply, demand (food, feed, fuel) and balance; in PgC per area unit; change 2000-2010.	X	X	-	2000 to 2010	1 km	22 countries in sub-Saharan Africa	• supply: satellite estimates (MODIS 17); • land cover sourcing of food, feed, fuel: MODIS (MCD12Cl); • demand: national statistics from FAOSTAT, with food, feed, fuel shares; • population density for spatial allocation of per-capita demand: CIESIN; • Balance: demand as % of supply.	NPP supply near constant. NPP demand increased from 19% to 41% of supply (2.2% per year). See Figure 12 for trends in the period 2000-2010.
Ardö, 2015	**NPP** supply and demand per capita; projection 2030.	-	X	X	2030	1 km	as above	• supply: average 2000-2010 estimated as in Abdi et al. and a 15 % reduction applied as effect of a severe drought in 2030; • demand: mean annual consumption of 2 t NPP per capita (Imhoff, Bounoua et al. 2004); • population density: as in Abdi et al. • population growth to 2030 based on low and high fertility scenarios: UN World Population Report; • vulnerability: very vulnerable if NPP per capita <1.25 MgC. Vulnerable if < 2.5 MgC. One MgC (Megagram) = 1 ton of C.	Depending on the fertility scenario, 150 (170) million and 68 (80) million living in very vulnerable and vulnerable areas respectively. See Figure 13. for spatial location of the areas.
Fetzel et al., 2012	**HANPP** in absolute terms (C/ha/yr) and as % of potential NPP. Also **eHANPP** (imported and exported biomass).	X	X	-	1980, 1990, 2000 and 2005	10 km	Africa & regions within (North, West, East, Central, South) and 10 selected African countries	The procedure is schematized in Figure 14. • NPPact: global estimates are from Haberl et al. (2007) and Erb et al. (2009) both derive their estimates from FAOSTAT statistics on crops; • NPP losses due to soil degradation are derived from the GLASOD dataset: http://www.isric.org/projects/global-assessment-human-induced-soil-degradation-glasod	+ 84% HANPP in West Africa from 1980 to 2005. Decreases in per capita HANPP in 3 Sahelian countries: Senegal, Chad, Nigeria (see Figure 15).

Source: Own elaboration, specific references indicated in table.

Table 3 Key studies using other approaches and a broader analysis of trends (Africa, SSA and the Sahel)

Key study	Metrics and Indicators	Trends			Time horizon	Spatial detail	Spatial Coverage	Modelling approach and main data sources	Key trends for SSA and the Sahel
		Past	Actual	Future					
Van Inttersum et al. 2016	**Self-sufficiency in five main cereals (maize, millet, rice, sorghum, and wheat)** = the ratio between cereal production and cereal demand. calories	X	X	X	2010- 2050	Country	Burkina Faso, Ghana, Mali, Niger, Nigeria, Ethiopia, Kenya, Tanzania, Uganda, and Zambia	Cereal demand (caloric content/maize equivalent) projected population increase and per capita consumption (projected income growth resulting in additional cereal demand for use as livestock feed and other purposes (partial equilibrium model for the agricultural sector IMPACT). Cereal production capacity on existing crop land through various degrees of yield gap closure and other strategic options (e.g., expanded irrigation area, increased cropping intensity, and crop area expansion). Main data sources were: United Nations (UN) population projections; FAOSTAT. Global Yield Gap Atlas	Currently (2010) SSA already imports about 20% of its five main cereal needs. Closing the existing yield gap alone on existing cropland area (from 20% to 50% or even to an optimistic 80%) is not expected to be enough to respond to future population growth to the year 2050. Both complex and uncertain additional agriculture developments such as intensification and full realization of irrigation potential are also needed to avoid a massive cropland expansion with associated environmental impact or vast import dependency, or both.
Paillard et al., 2014	**Biomass for food resource-use balance** **(Agrimonde)** kilocalories per capita availability and consumption, land use, Food consumption,	X	X	X	1961- 2003- 2050	Regions	MENA SSA, LAM, ASIA, FSU, OECD, World	Using the AGRIBIOM model, the objective is to balance food biomass resources and their use. FAOSTAT, with food, feed, fuel shares, population; GAEZ for potentially cultivable land.	At SSA level, the two scenarios developed (AGO and Agri1) indicate shortage of calories per person. This translated into a need to import calories from plants for food (5-50% of the needs). World needs by 2050 can be covered by transfers from surplus regions but this will depend on the evolution of diets and the reduction of waste.

	crop yields.								
Jalloh, A. et al., 2013	**Food vulnerability** Crop yields/area/ production/net exports/prices . Malnutrition rates and kilocalories per capita.	X	X	X	2000-2050	15-arc-minute (around 28 km) and countries	West Africa ECOWAS countries and Mauritania	Supply and demand modelled through: • Crop models (DSSAT) ; • Population projections; • GDP scenarios; • Climate change scenarios from GCM; • Partial equilibrium agricultural models. Spatial supply and demand based on spatial allocation models; Modelling for baseline, pessimistic and optimistic scenarios; Data from FAO, IFPRI (including MapSPAM) and country statistics.	Important changes (increase) in main crop yields, area and production (maize, sorghum, rice). Important changes (increase/decrease) in commodity prices. Important changes (increase/decrease) in malnourished children.
BAD and WWF, 2012	**Ecological footprint** Carbon, Forest, Cropland, Pastureland, Urban areas, Fisheries	X	X	-	1960-2008	Region/ Countries	Africa	• Ecological Footprint is an accounting framework on human demand for renewable resources and compares this demand with the bio capacity (regeneration capacities of the planet) or carrying capacity; • Data from GFN.	Africa's bio capacity increased by 30% in the last 40 years. Nevertheless values per capita are decreasing given the population dynamics, but not in a number of countries of SSA and Sahel.

Blein et al., 2008	**Production supply and demand** Crop and livestock production, agriculture trade, land and water availability; Food demand; Climate Change.	X	X	X	1980-2030	Region/ Countries	West Africa (ECOWAS)	• Food supply: Global and regional • Food demand: Global and regional • In the context of food demand, 4 main scenarios were defined (baseline, optimistic and 2 moderate scenarios) linked to specific assumptions on agriculture to calculate cultivated areas, crop and animal production, and irrigation; • Data from FAO.	Humid and semi-humid areas are playing a decisive role in regional agricultural dynamics. The region is improving its production capacities and has the necessary resources to achieve food security over the next 25 years. The proportion of imports is low. The region has still potential for agricultural growth. See Figure 17 for key scenario trends.
Africa Progress Panel, 2014	**Socio-economic development** World Bank OECD and IMF development indicators.	X	X	X	1990-2030	Region/ Countries	Africa	Flagship publication to identify and show main trends in development as policy recommendations.	Agriculture remains the Achilles' heel of Africa's development success. However it is possible to double agricultural productivity within 5 years, but the region is increasingly dependent on imports. SSA smallholders are a strength and potential source of growth. Yields of maize are expected to fall by around 22% as consequence of climate change.
Kessler, 1994	**Carrying capacity** maximum sustainable production levels (grain production, livestock units). Max. Population density.	-	X	-	1990	Regional	North and South Sahel, North and South Sudan	See Figure 18 for definitions. Author's data from different sources.	See Figure 18. for maximum sustainable production levels.

Source: Own elaboration, specific references indicated in table. The complete list of references from the review is presented as a commented list in Annex.

2.5 Implications and expected added value of this study

2.5.1 Approach to carrying capacity

A supply-demand model based on NPP is adopted in this study, using satellite derived NPP supply estimates following Abdi et al. (2014). This study also adopts the approach by Abdi et al. (2014) in estimating NPP demand, although taking into consideration also food and feed production imports and exports at national level (Fetzel, Niedertscheider et al. 2012). The balance between the two is an expression of the HANPP.

2.5.2 Time horizon and trends analysed

This study conducts an assessment for the current conditions as well as a forward estimate to the year 2050 taking into account both technological trends and the effect of climate change.

2.5.3 Spatial coverage and detail

As far as the modelling is concerned, the focus of the present study is the (entire) countries falling into the Sahel region. This study generates spatially explicit (gridded) results aiming at the most detailed resolution, while introducing specific information on crop types and management levels. It also aims at the identification of spatially explicit "hot spots" and possibly "hope spots" where to focus the analysis in terms of negative and positive trends.

2.5.4 Integrating agriculture in the scenarios

The approach proposed in this study intends to integrate detailed information on crops and related farm management in the scenarios narratives, drivers and elements. In order to assess current and future NPP in the light of alternative options specifically related to agriculture. In other words, the study pursues an orientation of the scenarios towards agriculture and food security, reflecting different agricultural options within (e.g. land use/land potential/crop choice/management).

2.5.5 Scenario drivers and narratives

In this study, narratives will be developed to support scenario modelling. This integration is intended for analysing and testing dynamics and linkages between and within agriculture scenarios, and namely to explore, identify and assess pathways, transitions, changes and tipping points (in a qualitative and/or a quantitative way).

To conclude, the main added values of the present study and its underlying model and scenarios can be ascribed to:

1. A re-assessment and improvement in the current NPP methodology based on the best and most objective available estimates of NPP supply and demand for the Sahel;

2. The ability of the model to estimate past and current levels of HANPP and to project them in line with the latest global change scenarios (e.g. climate, demography,) and expected impacts on the region, and in the context of spatially explicit alternative agricultural scenarios.

3 Methods and Scenarios of the Model

This second part of the report consists in the methodological section of the model. This prospective study looks to assess the balance of the biomass supply and demand of the Sahel to the year 2050. Stating with a baseline in 2012, the assessment is developed applying a net primary production (NPP) demand and supply model based on satellite derived NPP, the most reliable information on land cover, crop types and Land Utilisation Types (LUTs), as well as official production (including trade) statistics from FAOSTAT and UN population projections (See Figure 1). A specific question on how four alternative agriculture scenarios affect the Sahel's carrying capacity, given its variability and expected vulnerability to climate change (CC), is also addressed contrasting possible futures. Results are expressed in terms of the human appropriation of NPP (HANPP)are supported by scenario narratives.

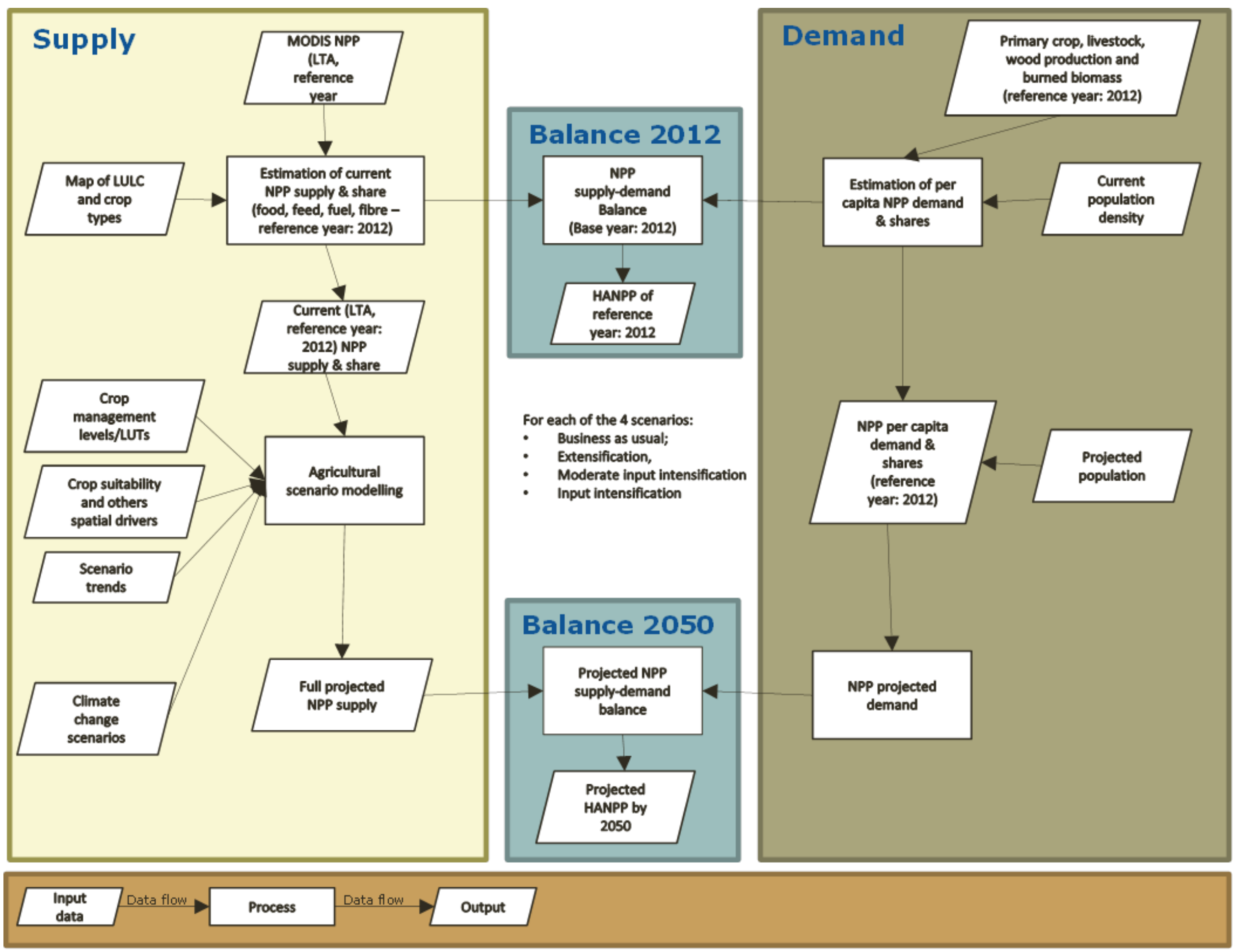

Figure 1 Diagram of the method to obtain the HANPP (C= carbon equivalent). Source: Own elaboration

More detailed flow diagrams illustrating key procedures used in the modelling are available in appendices.

3.1 The HANPP model: definitions and underlying assumptions

The approach to estimate of NPP supply and demand developed by the Lund University (Abdi, Seaquist et al. 2014) is regarded as appropriate for application at regional level (Running 2014) and is therefore adopted in this study. Additionally, alternative scenarios are developed to especially account for the agricultural dimension. The outcomes are spatially explicit indicators of the balance between NPP demand and supply, which are altogether the expression of the HANPP.

3.1.1 NPP supply

Satellite derived estimates are regarded as the most objective way of assessing NPP supply. In this study, despite known limitations, estimates of NPP derived from the satellite MODIS are used. Supply (and demand) of food (primary production minus crop residues), feed, and fuel are identified. Fibre is also computed among the supply shares although it does not have a correspondence in the statistical data used as input in the calculation of the demand shares.

The NPP supply shares are obtained superimposing to the satellite NPP estimates the most updated and reliable sources of relevant land use/land cover (LULC) and crop type data.

The main reference used in the proposed approach is the one developed in Abdi et al. (2014) with some adaptions. In terms of NPP demand, and notwithstanding known shortcomings in many national statistical systems, the mentioned work makes use of production statistics from FAOSTAT data as the best available proxy for carbon demand. This is under the assumption that most of the food produced in the region is consumed domestically. In this study, this assumption was tested by calculating, for each country, the difference between imports and export of relevant crops and commodities from the lasts statistics available from the FAOSTAT database. For this purpose the data provided in the trade section were used. Results are presented and commented in 4.10, where also issues related to urban versus rural consumption rates as well as to population projection, are discussed. A schematic representation of the procedure adopted is given in the appendices. The procedure includes the use of population density grids (from CIESIN, Columbia University) [7] and entails the estimate of the different NPP shares i.e. food (primary production minus crop residues), feed, fuel, as well as biomass burned for land clearing.

3.1.2 Modelling unit

The modelling unit is a mapping unit classified in terms of LULC (for the non-crop classes only) and crop types (for the crop classes only). In the latter case, attributes related to the farming and management level are explicitly associated to the crop. The combination of crop type-management level bring us close to the concept of land utilisation type (LUT) developed by the FAO.[8] This makes it possible to link the modelling unit with the agricultural scenarios and their development as it will be discussed later in more details.

3.1.3 Spatial extent

The study area includes whole countries with areas falling into the Sahelian zone. However, the definition of Sahel is not unambiguous. While it usually refers to the area comprised within a range of (minimum and maximum) rainfall isohyets, such isohyets vary according to sources. Moreover a southwards shift of the maximum rainfall isohyet has been observed which is ascribed to climate change. Depending on the sources the considered range varies between 200 and 600 mm or between 100 to 500 mm. In this study we have used the ranges defined by SDRN/FAO which are actually between 250 mm to 900.[9] The countries which have parts of their territory falling within the named ranges are Senegal, Gambia, Mauritania, Mali, Burkina Faso, Niger, Nigeria, Chad, Sudan, South Sudan, Eritrea, a total of eleven countries. Depending on the isohyets used also Algeria, Benin, Cameroun and Central African Republic have portions included in the Sahel, but have been excluded from this study

[7] http://sedac.ciesin.columbia.edu/data/collection/gpw-v3

[8] http://www.fao.org/docrep/x5648e/x5648e04.htm

[9] based on mean annual rainfall for the period 1960-1990.

due to the small size of the areas concerned. The island of Cabo Verde was also excluded. Nigeria was included in the aggregated analysis. It is true that, conventionally, only the extreme north of the country is regarded as part of the Sahel. However the shift of the 900 mm isohyet means that increasing portions of its territory are progressively becoming part of the Sahel. Nigeria is also important in the Sahel context due to the close economic links of its northern part with the neighbouring Sahelian countries. In any case the final scenario outcomes are also presented excluding Nigeria in order to better appreciate its contribution to the overall results. There are a few cases of disputed territories which have been included in the aggregated results but are excluded from the final reporting of the scenario outcomes at country level.

3.1.4 Spatial resolution

A 5 arc-minute grid cell (with a side of around 10 kilometres and an extent of around 10,000 hectares at the equator) is adopted as the spatial modelling unit. The lay-out and the resolution of the cells is that of MapSPAM. This level of analysis is chosen even if, in principle it would be possible to adopt a 1 km resolution cell as for the NPP satellite products, but this would give the false impression that crop type data have been rigorously downscaled at that level.

3.1.5 Time horizon

The agreed horizon for the study is 2050. This timeframe allows making assumptions in terms of climate change scenarios as well.

3.2 Scenarios

An original feature of this study compared with the previous HANNP studied, is in the provision of a number of agricultural scenarios. Four scenarios supported by narratives are developed; namely: Business as usual (BU), Moderate input intensification (MII), Input intensification (II), Extensification (EX). The mentioned scenarios are defined with reference to a baseline situation and described in terms of a number of assumptions and elements, as summarized in Table 4. These elements are further translated in the scenario modelling into quantitative targets (see Table 10). Scenarios are further implemented by means of a number of procedures and rules.

3.2.1 Scenario elements

The main scenario elements to be used in the modelling are the assumed trends in relation to:

- newly cultivated land, expressed as “targets”;
- newly irrigated land, expressed as “targets”;
- yields, also expressed as “targets”.

Targets are all expressed as percentage annual increases in respect to the baseline situation.

Other elements are part of the scenario narratives, e.g.:

- management levels (described in relation to yield levels: see above),
- relationship between crop farming systems and livestock raising,
- other assumptions at macro level (market integration and trade, GDP growth, etc.),
- other indicators (environmental impacts, farming costs, etc.).

3.2.2 Scenario targets

Targets for new irrigated areas (from newly cultivated land and from previously rainfed land) and new rainfed areas are set based on specific scenario trends. These are met based on a selection of the cells according to their suitability values. For instance an expansion target for total irrigated land is set in the II or MII scenario based on the specific scenario trends. The target is met by progressively selecting the cells with the higher suitability rankings until the total cell area matches the target. It is also possible to look at the HANPP balance (the degree of coverage of NPP demand by supply) as a scenario target, although as an ex-post analysis: in this case, if achievable, the target is met selecting all cells with the corresponding suitability values until their total NPP production (total cell area times yields) equals the demand.

Target yields are also defined. First, an "overall yield target" is defined which expresses the potential for yield improvement relative to the different scenarios (II having the highest potential and EX the lowest) and reflects the general technological assumptions underlying each scenario. A number of assumptions are made behind the technological trends in each scenario, related to management levels and key choices. These are part of the narratives and describe input levels and general farming practices making possible the change in yield levels. Second, specific yield targets are defined for reference crops reflecting both the effect of climate change and the technological trend assumed in each agricultural scenario. For non-crop LUTs there are no yields and management levels defined and the two remain unchanged from the baseline to any of the scenarios.

3.2.3 LUT transitions

LUT transitions are changes from the current (baseline) crop and non-crop LUTs as described earlier, to those in one of the scenarios defined above. We consider three possible transitions: 1) expansion of irrigated areas (from LUTs in non-cropped or from crop-LUTs in rainfed areas) 2) expansion of rainfed areas (from non-cropped areas) and 3) intensification (transitions from one rainfed crop to the other and/or between different management levels).[10] The model follows the sequence: 1) first the candidate cells for new irrigation are selected, 2) then, over the remaining non-cropped areas, the candidate cells for rainfed expansion are selected, and 3) finally, over the remaining rainfed cropped areas, transitions in terms of management levels are modelled. Possible LUT transitions are subject to specific conditions-rules.

3.2.4 LUT transition rules

Rules for the transitions of the LUTs above are applied to the crop specific suitability map products elaborated in GAEZ (see appendices). This is a suitability based on bio-physical criteria and is defined separately for irrigated and rainfed cropping conditions. The extent of the final transitions depends on the scenario targets.

3.3 Crop suitability

Crop suitability is measured for a set of crops[11] in terms of eight ordinal suitability classes, from very high to not suitable and differently for irrigated and rainfed conditions.

Each cell is a "candidate" for expansion of either irrigated or rainfed land or for transition between rainfed crops if it is suitable for at least one crop. For new irrigated areas, we assume that transition will take place in all the areas (cells) where any of the suitability maps has a valid value (classes 1 to 7). In case of more crops being suitable for the same cell, the crop with the maximum suitability class is selected. After the application of the rules above, each cell will be also identified by a suitability value for a specific crop (separately for irrigation and rainfed conditions).

[10] Only transitions in management level were considered. Assumptions on actual crop selection are beyond the scope of the present study, although could be considered in the future.

[11] Only major crops, strategically important for the study area, were considered. These include rice and sugarcane as irrigated crops and sorghum, millet, cassava, yam, groundnuts, maize, beans, cotton as rainfed crops.

3.4 Livestock

Possible relations between livestock and crop farming are accounted for in the scenario assumptions and further analyzed based on the scenario outcomes. Relations can be either regarded as positive, namely reinforcing cropping systems in the management of their soil fertility, or negative, due to encroachment and competition for livestock feed (crop residues, fallows) and water, or due to direct damages caused by animals to the crops, etc. This applies especially to mobile livestock systems (transhumant or nomadic, or so called "only grazing" systems) in the northern areas of the Sahel and to a lesser extent to seasonally mobile livestock systems in the southern part of the Sahel (rainfed and irrigated mixed crop–livestock systems) as classified by Robinson et al. (2011).

Such relationships are included in the narratives for the different scenario (mainly in terms of stronger or weaker integration between crop and livestock systems). They apply at both territorial level through, for instance, improved livestock lending management, common social organization for water, pastures, better market integration, and farm level through improved soil fertility management or specific herd management actions (e.g. decrease in grazing cattle number and increase in sedentary draught and fattened cattle and in small ruminants). The type of effect and the degree of such relationship is further evaluated by superimposing gridded densities of livestock to the maps of the expansion areas (irrigated and rainfed) which is one of the outcome of different scenarios. This procedure allows singling out a specific set of potential "hot spots" or "hope spots", also depending on the scenario assumptions. For scenarios MII and II, to a lesser extent, the assumption is that the areas identified (with a focus on higher cattle densities) are "hope spots" that will experience positive synergies both a territorial and farm level. For scenarios BU and EX, the underlying assumption is that a lowest degree of integration between crop and livestock systems will be attained, leading to even more conflicts with sedentary farmers than at present, owing to competition for water and pasture resources. Therefore the locations identified by intersecting high livestock density areas and cropping expansion areas, can be qualified ad "hot spots". A limitation in the analysis above is that we are using cattle densities referring to the current situation while scenarios are projected to the year 2050. A projection of the present population densities however, is beyond the scope of this study.

3.5 Scenario outcomes

The outcomes of each scenario include indicators relating NPP supply and demand (i.e. the HANPP) for the different shares or component (food, feed, fuel). This is done for the baseline situation and as predictions to the year 2050 which take into account the effect of crop productivity technological trends and climate change. Other implications (in terms of environmental impact, farming costs, and relation between cropping system and livestock) are described in support of the scenario modelling narratives and results.

Outcomes are reported for the whole spatial extent of this study, per country and per agro-ecological zone (AEZ). This is done both in the form of summary tables as well as though maps.

In addition, "hot spots" and "hope spots" are identified, mapped and discussed in a dedicated section. These are defined in two ways: in the first case based on the relation between NPP supply and demand and in the second case specifically for identifying areas of possible conflict or complementarities between livestock and cropping systems. "Hot spots" represent areas of concern, where a combination of intermediate to very high NPP demand and intermediate to very low NPP supply is found.

Then, in the case of livestock, where high cattle densities are combined with new land development (irrigated or rainfed) envisaged by the different scenarios: hence, especially in relation to transhumant pastoralist systems, a possible condition of conflict or of synergy, depending on the assumptions underlying the different scenarios.

Table 4 Scenario elements and assumptions

Scenarios	Yield trends[12]	Trends in new rainfed crops	Trends in irrigated crops	Other indicators (environmental impacts, farming costs, relation with livestock)	Other assumptions at macro level (market integration and trade, etc.)
Baseline	Recent trends [13].	Recent trends.	Recent trends	Reference years	Reference years
BU	Recent trends plus an improvement in the same trend. ++	Recent trends plus improvement. +	Recent trends plus improvement. ++	Current (or from recent trends) environmental impacts and farming costs. Limited degree of integration between crop and livestock systems.	As in reference years (see the increase in imports and prices in the 90s; for the 00s increase in exports, decrease in commodity prices).
II	II trends. ++++	II trends. ++	II trends (largest increase in irrigated land). ++++	Higher environmental impacts and farming costs. Higher degree of integration between crop and livestock systems.	II trends (increase in food production, and export biofuels).
MII	MII trends. +++	MII trends. +++	MII trends (increase in irrigated land, but smaller than II). +++	Lower environmental impacts and farming costs. Highest degree of integration between crop and livestock systems.	MII trends (increase in food production, export commodity surplus).
EX	As in recent trends (but no additional improvement, thus less than BU). +	EX trends. ++++	Close to recent trends, but increase less than BU. +	Higher environmental impacts related to land clearing; otherwise as for BU. Lowest degree of integration between crop and livestock systems. More conflicts with sedentary farmers owing to competition for water and pasture resources.	Recent trends on export increase in particular biofuels.

Source: Own elaboration.

[12] The number of + indicates the order of magnitude among scenarios: + lowest, ++++ highest.
[13] Period 2000-2011.

4 Model Implementation

4.1 Calculation of the reference NPP supply and "shares"

As anticipated, NPP supply is derived from MODIS satellite data for a reference period. Each modelling unit (cell) in the study area spatial extent is given the average NPP value extracted based on the percentage of the different land uses/land cover (LULC) in the cell. These percentages are obtained from the combination of:

- Data sources providing a number of relevant land uses/land cover (LULC) for the non-crop classes;
- Detailed crop types for the crop classes.

Subsequently, the percent allocation in terms of the different NPP "shares" (food, feed, fuel, fibre) is derived for each LULC or crop type. Also LULC classes which are regarded as not sourcing NPP (e.g. barren land, built-up areas) are taken into account.

Especially in the Sahelian context, a specific LULC or crop type can source more than just one component or "share". For instance crops can source food, feed and fuel. Forest land and woodlands can source feed and fuel (and food as well especially in situations of acute food shortage). In the present study, for each class in the LULC and crop type classification, assumptions on the different components are made based on available literature. These assumptions are then applied for the whole study area (in a "blanket" approach) although sensitivity analyses always remain possible for testing the parameters used.

Crop types are further defined in terms of their management level: the combination of the two gives a "land utilisation type" (LUT).[14]

4.1.1 Map of the Land Utilization Types

Non crop LUTs

As to the non-crop classes, the classification in Abdi et al. (2014) is used, also to facilitate the comparability of results. This is an aggregation of International Geosphere–Biosphere Programme (IGBP) classes[15] based on the MODIS Land Cover Type Product (MCD12Q1).[16] The class "cropland" is broken down into crops or crop groups, as it will be discussed in the next sections.

The classes are summarized in Table 5:

[14] The term LUT is extended to non-crop classes in the remaining of this study.
[15] International Geosphere–Biosphere Programme: http://www.igbp.net/
[16] https://lpdaac.usgs.gov/

Table 5 Classification for non-crop LULC classes (class 12 & 14 excluded)

Class	IGBP Class	Merged Class
1	Evergreen Needleleaf forest	Forest
2	Evergreen Broadleaf forest	
3	Deciduous Needleleaf forest	
4	Deciduous Broadleaf forest	
5	Mixed forest	
6	Closed shrublands	Woodland
7	Open shrublands	
8	Woody savannas	
9	Savannas	Grassland/Savanna
10	Grasslands	
11	Permanent wetlands	Not Included
12	Croplands	Cropland
14	Cropland/Natural vegetation mosaic	
13	Urban and built-up	Not Included
15	Snow and ice	
16	Barren or sparsely vegetated	
255	Fill Value/Unclassified	

Source: Abdi et al; (2014) Supplementary data. (http://iopscience.iop.org/1748-9326/9/9/094003/media/erl500220suppdata.pdf).

Classes excluded

A number of LULC classes are excluded from the analysis based on the assumption that they are not generating land-based NNP (permanent wetlands, urban and built-up, barren or sparsely vegetated).

Crop LUTs

MapSPAM (2005 version) by HarvestChoice-IFPRI[17] is one of the few sources providing spatially explicit estimates of cropped areas[18] and production for different crops and four

[17] HarvestChoice, 2014. 'What's New with SPAM Two (Thousand Five).' International Food Policy Research Institute, Washington, DC., and University of Minnesota, St. Paul, MN. Available online at: http://harvestchoice.org/node/9613 .

[18] More precisely MapSPAM provides estimates of harvested areas (summing-up areas in case of multiple cropping) as well as physical cropped areas. The latter estimates were used in this study.

management levels: irrigated, high input rainfed, lows input rainfed and subsistence. This is equivalent to the LUT concept described earlier.

Data comes as a downloadable vector grid of cells[19]. The bundled data for SSA was filtered to retain only the cells in the selected spatial extent (corresponding to the selected Sahelian counties as mentioned earlier). There are a total of 108,322 cells in the “Sahel mask”. Only around 36.000 cells have at least one crop (i.e. a physical cropped area > 0 %).

The products by MapSPAM have been assessed by IFPRI and although acknowledging limitations in some of the datasets used for SSA (above all due to the quality of official crop area and production statistics for a number of the countries concerned), were judged to be of sufficient quality (You, Wood et al. 2009).

The MapSPAM datasets records 40 crops in the study area. These are further specified in terms of the management levels already cited. Even when excluding the crops/management levels which do not occur in the database, there are around 135 valid combinations. These have been further grouped in a smaller number of meaningful crop types (fifteen) and management level (three) combinations. A larger number of combinations would not be supported by adequate data in successive stages of modelling (namely in making assumptions on targets yields based on technological trends and climate change effects).

The following table 6 gives a summary of the combinations retained.

[19] http://mapspam.info/bundle-data/

Table 6 Crop LUT grouping

N.	Crops Code	mapSPAM crop types Name	Corresp. ICC class	Management levels (occurrence in the mapSPAM for Sahel) h rainfed high inputs	l + s > l rainfed low inputs & subs.	i irrigated	Grouping N.	Final crop types	Short	Management levels h rainfed high inputs	ls rainfed low inputs & subs.	i irrigated
7	sorg	sorghum	Cereals	x	x	x	1	**sorghum**	SORG			
3	maiz	maize		x	x	x	2	**maize**	MAIZ			
5	pmil	pearl millet		x	x	x	3	**millets**	MIL			
6	smil	small millets										
1	whea	wheat				x	4	**wheat**	WHEA			
8	ocer	other cereals			x		5	**other cereals (including barley)**	OTHC			
4	barl	barley										
2	rice	rice			x	x	6	**rice**	RICE			
9	pota	potatoes	Root/tuber crops	x	x	x	7	**roots/tubers crops**	RTC			
10	swpo	sweet potatoes										
11	yams	yams										
12	cass	cassava										
13	orts	other roots and tubers										
14	bean	phaseolus beans(dry)	Leguminous crops	x	x	x	8	**leguminous crops**	LEG			
15	cowp	cowpeas										
16	opul	other pulses										
19	cnut	coconuts	Permanent oilseed crops	x	x	x	9	**permanent oilseed crops**	POIL			
20	oilp	oilpalm										
21	sunf	sunflower	Oilseed crops	x	x	x	10	**oilseed crops**	OILC			
22	sesa	sesame see										
17	soyb	soyabeans										
18	grou	groundnuts										
23	ooil	other oil crops										
24	sugc	sugarcane	Sugar crops			x	11	**sugarcane**	SUG			
25	cott	cotton	Fiber crops	x	x	x	12	**fibre crops**	FIB			
26	ofib	other fibre crops										
27	coco	cocoa	Beverage and spice crops	x	x	x	13	**Beverage, Fruits, Nuts crops**	FRUIT			
28	teas	tea										
29	bana	bananas	Fruit and nuts									
30	plnt	plantains										
31	trof	tropical fruit										
32	temf	temperate fruit										
33	vege	vegetables	vegetables and melons	x	x	x	14	**vegetables and melons**	VEG			
34	toba	tobacco	other crops	x		x	15	**other crops**	OTHE			
35	rest	rest of crops										
		COMBINATIONS:	**45**									

Source: Own elaboration, based on HarvestChoice-IFPRI (2014)

Further, we identified the dominant crop LUT in each cell. The dominant crop LUT was assigned the percentage of the total cropped area in that cell.

The next step was to find the remaining percentages of each cell, which are represented by non-crop LUTs and classes excluded from the calculation. Also in this case we considered only the dominant non-crop LUT in each cell.

The final data elements include:

- CropLUT: the dominant crop LUT in the cell;
- PerCrop: the percentage of all crops LUTs in the cell, assigned to the dominant one;
- noCropLUT: the dominant non crop LUT in the cell (classes are: 1,2,3,999); [20]
- PerNonCrop: the percentage of all non-crop LUTs in the cell, assigned to the dominant one;
- PerExclud: the percentage of the excluded classes;
- Tot: the sum of the percentages.

4.1.2 Definition of the supply shares of the different LUTs

The different supply shares (food, feed, fibre, and fuel) are "sourced" differently by crop and non-crop LUTs. For crops, the contributions of food, feed and fibre were calculated based on Wirsenius (2000) and Haberl et al. (2007) providing percentages of harvested products compared to residues (harvest index) specifically for Sub-Saharan Africa. More recent general literature exists such as Scarlat et al. (2010) but no specific studies for the Sahel region were identified. Given the peculiarities of the cultivars used in the region it was judged more suitable to refer to the early references.

We have also made specific assumptions for other crops not cited in the literature and non-crop LUTs. The table below summarizes the assumptions made. This was then used to calculate the shares per each cell and LUTs within.

[20] Class 4 (cropland) is not considered because the share from the crop LUT is retained.

Table 7 Supply shares for the crops and non-crop LUTs selected

N.	Crops	Short	NPP supply shares: Food	Feed	Fiber	Fuel	Total	harvest index, i.e. ratio between :	source	remarks
1	sorghum	SORG	22%	78%	0%	0%	100%	grain:straw	Wirsenius , 2000	
2	maize	MAIZ	22%	78%	0%	0%	100%	grain:straw	Wirsenius , 2000	
3	millets	MIL	22%	78%	0%	0%	100%	grain:straw	Wirsenius , 2000	same as for sorghum
4	wheat	WHEA	30%	70%	0%	0%	100%	grain:straw	Wirsenius , 2000	
5	other cereals (including barley)	OTHC	35%	65%	0%	0%	100%	grain:straw	Wirsenius , 2000	barley
6	rice	RICE	40%	60%	0%	0%	100%	grain:straw	Wirsenius , 2000	paddy
7	roots/tubers crops	RTC	50%	50%	0%	0%	100%	tuber:top	Wirsenius , 2000	
8	pulses	LEG	30%	70%	0%	0%	100%		Haberl et al., 2007	
9	permanent oilseed crops	POIL	42%	58%	0%	0%	100%	fruit bunch:leaves	Wirsenius , 2000	oil palm
10	oilseed crops	OILC	40%	60%	0%	0%	100%	pod:stalk	Wirsenius , 2000	groundnut
11	sugarcane	SUG	60%	40%	0%	0%	100%	stem: top/leaves	Wirsenius , 2000	
12	fibre crops	FIB	0%	20%	80%	0%	100%		our estimate	as for cotton but at full growing stage
13	beverage, Fruits, Nuts crops	FRUIT	30%	70%	0%	0%	100%		Haberl et al., 2007	
14	vegetables and melons	VEG	30%	70%	0%	0%	100%		our estimate	as for pulses
15	other crops	OTHE	80%	20%	0%	0%	100%	tobacco	our estimate	non-food
	Non-crops									
16	forest	FOR	0%	0%	0%	100%	100%			trees canopy cover > 60%
17	woodland	WOOD	0%	30%	0%	70%	100%		our estimate adapted from IGBP	tree shrub canopy cover > 30% < 60%, i.e. 45% on avg
18	grassland/savanna	GRSAV	0%	70%	0%	30%	100%			tree and shrub cover < 30%
19	excluded	EXCL	0%	0%	0%		0%			

Source: Own elaboration, based on Haber et al. (2007), HarvestChoice-IFPRI (2014), Wirsenius (2000).

4.1.3 MODIS derived NPP supply data

The MODIS Terra/MOD17A3 satellite product[21] provides an annual estimate of NPP supply expressed in terms of kg C. It is a gridded product with a 30 arcsec resolution (around 1 km at the Equator). The global mosaic image with average values for the years 2000 -2014 is used in order to refer to a long term average (LTA) as the basis for the NPP supply calculations.[22] It was not possible to analyse yearly values in order to take into account also the inter-annual variability of NPP, although this could be considered in future studies.

A number of pixels without valid NPP data are coded as indicated below:

Table 8 MODIS classes with 0 or no valid NPP values

Value	Description
65535	Fill value: conventional HDF-EOS fill value assigned to non-modeled pixels not falling into other categories below.
65534	Perennial salt or inland fresh water body cover type.
65533	Barren, sparsely vegetated (rock, tundra, desert) cover type.
65532	Perennial snow or ice cover type.
65531	Permanent wetlands/inundated marshland type.
65530	Urban/built-up cover type.
65529	Unclassified pixel.

Source: NASA /USGS (nd) Land Processed Distributed Active Archive Center (LP DAAC) https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mod17a3

The image was reclassified attributing a value = 0 to the records above and the average NPP value was further assigned to each cell.

4.1.4 Allocation of the different shares of NPP

For each cell and according to a) the percentages of crop and non-crop LUTs as well as of areas excluded from the evaluation and b) the shares in Table 7, the average value of NPP was allocated in terms of the supply components food, feed, fibre, and fuel.

[21] https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mod17a3

[22] The product can be downloaded from http://www.ntsg.umt.edu/project/mod17. /pub/MODIS/NTSG_Products/MOD17/GeoTIFF/MOD17A3/GeoTIFF_30arcsec

4.2 Projection of NPP supply

The effect of climate on current NPP supply values was taken into account in order to reflect climate change (CC) trends. This is in relation with the food and fibre shares only, while the effect on the remaining components was not accounted for. Two CC scenarios were initially taken into consideration based on the representative concentration pathways or RCPs adopted by the IPCC for its fifth Assessment Report in 2014.[23] The mentioned scenarios superseded the Special Report on Emissions Scenarios (SRES) projections published in 2000. The assumption was to select greenhouse gas concentration scenarios which represent "contrasting" conditions and namely a more "optimistic" scenario (RCP4.5) and a more "pessimistic" one (RCP8.5). These refer, respectively, to radiative forcing values of +4.5 and +8.5 W/m2 in the year 2100 relative to pre-industrial values.

However, there are only a few studies investigating the impact on crop production which are based on the more recent RCPs. Rosenzweig et al. (2014) for instance, projected changes globally using different GCM and crop models. For tropical areas they concluded that maize production could decrease by 3-10% and rice by 2-5% by every degree of warming during the 21st century. Ramirez-Villegas and Thornton (2015) obtained yield reductions of dry beans by the 2050s for RCP8.5 in Africa. Yield decreases of 40% and more were projected over large areas of the Sahel. Havlík et al. (2015) extended the analysis to encompass specific Shared Socio‐Economic Pathways (SSP) and namely SSP4 and SSP5. In this context they referred to RCP2.6 and RCP8.5 and to specific GCM to predict, using the EPIC model, crop yield losses. Sub‐Saharan Africa was found to be among the most impacted areas in 2030 but with CO2 effects, impacts are assumed to be limited. Impacts are more pronounced by 2080. Without CO2 effects, these impacts are expected to more than double in the same time horizon. For RCP8.5 with CO2 effects average impacts on crop yields can be as severe as ‐15.2% for Sub‐Saharan Africa.[24] Looking at specific crops, rice is expected to be impacted negatively (‐8.6%) as well as groundnuts (up to ‐49.1%).

Sultan et al. (2014) investigate the impact on sorghum yields under the RCP8.5 scenario. Climate change leads to a decrease in sorghum yields everywhere in West Africa and the coefficient of variation of yields increases as well. In response to such climate change, but without accounting for direct crop responses to CO2, mean crop yield decreases by about 16-20% and year-to-year variability increases in the Western part of the Sahel, while the eastern part sees much milder impacts. The studies above, while providing very useful insights, do not offer a coherent set of references which will make them immediately usable in this study (not having the same time horizon or the spatial extent, not providing homogeneous references for at least a number of key crops).

SRES scenarios remain valid, to a certain extent, under the new RCPs and SSP scenarios under which conditions more relevant studies on the impact on crop yield can be found. A number of researches have investigated relations between the two types of scenarios. Rogelj et al. (2012) for instance, conclude that although the RCPs were not developed to mimic specific SRES, pairs with similar temperature projections over the twenty-first century can be found. RCP 8.5 would yield temperature projections close to those of the SRES A1FI scenario ("pessimistic") while RCP4.5 temperature projections are similar to those of SRES B2 ("optimistic"). Regarding rainfall finding consensus for future projections is more problematic, as large uncertainties are found in the modelled precipitation changes, especially in areas such as the Sahel (Dosio and Panitz 2016). Nevertheless, the cited work by Sultan et al. (2014) indicates that most studies suggest that temperature increase is the main driver of adverse yield changes in the future for West Africa.

[23] https://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml

[24] With reference to the 18 species represented in the GLOBIOM model, aggregated in terms of dry matter.

The GAEZ project[25] provides useful references in the form of potential yield predictions obtained through crop simulation models, for different crop types and under a number of SRES scenarios and GCMs. This is especially the case for the B1 scenario (for its coherence with RCP4.5) and for the A1FI one (for its coherence with RCP8.5). The simulations provided in GAEZ come with the two variants of carbon fertilization. Modelled yields from GAEZ were calculated over the whole of the Sahel spatial extent using the HadCM3 CGM[26] and the B1 and A1FI SRES scenarios for a number of crops. However the yield reductions for 2050 returned contradictory results with reference to the emission scenarios adopted and would deserve more in-depth evaluations before they can used as inputs in our model.

Specific references to the West African context and crops are given by Zougmoré et al. (2015). Based on previous work by Nelson et al.(2010), Jalloh et al. (2013), and Thomas and Rosegrant (2015), the authors have estimated yield reductions for the year 2050 for a number of crops including irrigated rice (-19%) and rainfed sorghum (-13.9%). Key figures are indicated in Table 9. These reductions were computed by means of the DSSAT crop simulation model under the SRES A1B scenario and averaged based on a number of GCMs.

Similar results are reported in the publication by Thomas and Rosegrant (2015)[27] again for West Africa and for the time horizon 2000-2050: namely -5.6% for groundnut, -18% for irrigated rice and -13% for rainfed sorghum[28]. Slightly higher figures (- 17%) are reported by Schlenker and Lobell (2010) under the A1b scenario, although with reference to the whole SSA.

We have finally decided to use the figures in Zougmoré et al. (2015) with the exception of millet (from Knox et al. (2012)) as references in this study for expressing the future reduction in the NPP supply as the effect of climate change.

When estimating the projection of the NPP supply to the year 2050 the effect of climate change should be compounded with the one of technological improvements. Zougmoré et al. (2015) also estimated yield increases for 2050 due to the sole technological trends through the IMPACT model.[29]

Estimates due to both technological trends under the assumption of optimal management conditions and the effect of climate change under a specific emission scenario (SRES A1B) are summarized in Table 9.

The net effect for the different reference crops is therefore taking into account both the yield increases in the technological trend and the impact of climate change (which, based on the cited authors' estimates, are all in terms of decreases in yield). The negative effect of climate change on crop yields can be actually seen as the combination of two types of factors: the so called "yield defining" factors and the "yield limiting" factors (Tittonell and Giller 2013). Yield limiting factors cause a reduction of crop biomass due to water and nutrient availability.

The action of yield defining factors is such that it limits the full genetic potential of a specific crop and variety (e.g. in relation to the optimal use of water and chemical fertilization). This

[25] Global Agro-ecological Zones (GAEZ v3.0), 2010, FAO, Rome, Italy and IIASA, Laxenburg, Austria.

[26] This CGM was developed at the Hadley Centre in the United Kingdom.

[27] Climate change impact on key crops in Africa: Using crop models and general equilibrium models to bound the prediction. In: FAO 2015. Climate change and food systems: global assessments and implications for food security and trade. Food Agriculture Organization of the United Nations (FAO).

[28] Similar figures for yield reduction in Sorghum are also suggested by Knox et al. (2012).

[29] This is a global partial equilibrium food and agricultural model developed by IFPRI: http://www.ifpri.org/program/impact-model

is for instance the case of high yielding varieties, especially of maize and irrigated rice, assumed to be used in the Input Intensification (II) scenario.[30]

Both these effects are captured in the third column of Table 9 and apply to all crops/varieties regardless of the scenario adopted.

Table 9 Yields predictions for West Africa and the Sahel

	Yield variations from 2000 to 2050 (in %)[31]		
Reference crop	**Due to technological trend**	**Due to the effect of climate change**	**Net effect (technological trend minus effect of CC)**
Groundnut	+40	- 7	+ 33
Maize	+60	- 5	+ 55
Rice (irrigated)	+90	-19	+ 71
Sorghum	+94	-14	+ 80
Millet	+147	-11	+136
Cotton	+91	-81	+ 10

Source: Knox et al. (2012) and Zougmoré et al. (2015)

The yield variations above are applied to the current levels of the NPP food and fibre supply components, in order to project the NPP values to the year 2050.

As anticipated this is done in two steps:

First the "overall yield target" for a scenario is taken: see the paragraph on Scenario Modelling for a description and Table 10 for a synthesis of the targets. We consider the II scenario targets as the benchmark and apply in this case the full (100 %) net increases for the different reference crops as defined in Table 9.

For the other scenarios we proportionally reduce the yield increases based on their respective overall yield targets. For instance, the increase in sorghum in the MII scenario will be equivalent to around 63% of the one in the II scenario (given the respective overall targets of and 2.5% and 4%), or 63% of the net increase (technological trend minus CC) of 80% as specified in Table 9.

A model run was also performed, for all scenarios, assuming no reductions due to the effect of climate change (Scenarios "without climate change"). Only for the II scenario and with reference to the mentioned high yielding varieties of maize and irrigated rice, different yield variations were assumed in this case. The yield variation over the time horizon due to the sole technological trend was increased of around 20% for both crops (maize +70% and irrigated rice + 100%).

[30] See for instance Schlenker and Lobell (2010).

[31] All references are from Zougmoré et al. (2015) but for the case of millet (from Knox et al., 2012).

4.3 Scenario narratives

The agricultural scenarios are supported by narratives, i.e. more general qualitative descriptions including relevant contextual information such as those related to external drivers.

From the modelling perspective, scenarios can be treated either as:

- independent and mutually exclusive (i.e. one scenario applied to all modelling units at the time);
- specific pathways (or trajectories) over time and space, possibly comprising coexistence and transitions from one scenario to the other (e.g. trapped transitions, tipping points, alternative pathways). In this case each modelling unit is evaluated separately in terms of its pathway.

Specific pathways are analysed in relation to the "hot spots". The possibility of introducing them in the modelling was also considered, but found to be beyond the scope of this particular study.

4.4 Scenario modelling

This section describes how the elements and assumptions initially defined for the different scenarios as well as for the baseline have been translated into transition and allocation rules (of new irrigated and rainfed areas) based on specific targets (see Table 10 for a summary). The areas resulting from this scenario specific allocation processes are the basis for calculating the projected NPP supply based on yield targets. The targets presented here will be further contextualised with additional socio-economic, production and climate considerations in the section dedicated to the narratives.

4.4.1 LUT transitions and area allocations

The following LUT transition rules are applied for all scenarios, and implemented through a number of spatial and non-spatial queries using the GIS software ArcGIS and QGIS and MS Access. A diagram of the procedure applied in the spatial allocation is provided in the appendices.

Step1: Irrigation area expansion

The initial basis for evaluation is given by all current non-Crop LUTs and rainfed crop LUTs, while currently irrigated crop LUTs are excluded (masked out). We assume that the expansion can take place in all the areas (cells) where any of the suitability maps for irrigated crops has a valid value (classes 1 to 7). In case more crops have a suitability value in the same cell, the max suitability is taken. There are two possible cases:

- From non-crop LUTs (e.g. from grassland/savannah) to irrigated crop LUTs, (e.g. to irrigated rice)
- From rainfed LUTs (e.g. from sorghum, low input) to irrigated LUTs (e.g. to irrigated vegetables).

We obtain cells that are "candidates" for the expansion of the irrigated areas and we then select among them based on the suitability for selected crops in order to fulfill the scenario target for irrigated areas.

Step 2: Rainfed area expansion

The outcome of step 1 is merged with the currently irrigated LUTs and is therefore a mask for the further expansion of the rainfed area, which in principle could occur in all remaining non crop LUTs; e.g. from woodland to rainfed cotton.

We assume that this expansion occurs where any of the suitability maps for rainfed crops has a valid value. We obtain cells that are "candidates" for the expansion of the rainfed areas and we then select among them based on the suitability and the accessibility for selected crops in order to match the scenario targets for the same rainfed areas.

Step 3: Intensification

The outcome of step 2 is a mask for all remaining crop-LUTs cells where no expansion (of neither irrigated nor rainfed areas) takes place but solely intensification. For these remaining cells we assume that crops will remain unchanged but yields will increase (e.g. see BU yields earlier); the management level changes accordingly from the current (baseline) conditions to those specified for the relevant scenario.

The final product is a map of cells that are "candidates" for the expansion of the irrigated or rainfed areas plus the changes in yield/management levels in all the remaining currently cropped areas. The suitability class value and the crop type are retained.

For all scenarios we also consider that:

- Farmers tend to adopt single measures, not necessarily the "full" packages. It is assumed that, when referring to the management levels associated to each scenario, at least the most important ones are adopted by the farmers;

- A number of environmental impacts which go beyond NPP supply (soil fertility and degradation, pollutants, CO2, biodiversity, other externalities, etc.) and effects in terms of farming costs are also highlighted and elaborated further in the narratives;

The end result is the "scenario composite" of all possible cases occurring; namely:

- Expansion of irrigated areas;
- Expansion of rainfed areas;
- Intensification on irrigated areas;
- Intensification on rainfed areas;
- Unchanged (Natural vegetation, i.e. non-crop LUTs);
- Not evaluated.

When all transitions are defined for a specific scenario and depending on the outcome of the transitions, the yield targets projected for the year 2050 are applied: this is achieved by increasing the current NPP food and fibre shares by the % variations defined in the previous paragraph.

4.5 Baseline

The baseline situations constructed on the basis of the following data sources:

- the current area distribution of crop and non-crop LUTs, derived from the MapSPAM 2005 version;
- reference management levels, the crop LUTs, defined as above;
- reference yields: related to the NPP food shares derived from the long term averages (2000-2014) of the MODIS satellite time series;
- NPP demand based on the most recent FAOSTAT data, i.e. 2012.

Conventionally we assume that the reference year for our baseline is 2012.

The baseline situation assumes trends calculated from FAOSTAT and other sources over a long enough period (usually 2000-2010 or 2011). Such trends do not represent an input in the modelling but simply a reference for comparison with the other scenarios.

Baseline profile:

Reference yields: increase of 0.5 %/year
Management levels: current (as defined in MapSPAM consistently with the GAEZ suitability)
Reference irrigated area expansion: increases of 1 %/year
Reference rainfed area expansion: increases of 1-1.5 %/year
Sources: FAOSTAT statistics from 2000 to 2011, AGRA (2014) and Blein at al. (2008).

4.6 Business as usual (BU)

The BU scenario assumes the same trends defined in the baseline, also accounting for an improvement due to an expected further technological improvement.

BU profile:

Target yields: increase of 0.75 %/year.
Management levels: current, plus a further technological improvement
Management level transitions: from current to BU
Target irrigated area expansion: increases of 1.2 to 1.5 %/year
Target rainfed area expansion: increases of 1.75 %/year
Relations between crop and livestock systems: limited degree of integration between crop and livestock systems. Change in livestock species contribution to herd composition. More small ruminants and less cattle owing to decrease in grass availability.
Other indicators: current environmental impacts and farming costs
Sources: FAOSTAT statistics, AGRA (2014) and Wiggins (2014).

4.7 Input intensification (II)

Here the underlying assumption is the adoption of agricultural technologies for crop production intensification with an emphasis on "Green revolution" solutions, i.e.: high-yielding cultivars (implying improved seeds), synthetic fertilizers, irrigation, and (conventional) pest and weed control, with higher application intensities than for MII. [32] As mentioned, consideration is given also to the negative effect of climate change on such high yielding varieties due to temperature increases and reduced water availability: the assumed yield targets reflect this specific effect. Expansion of cultivated land outlined in this scenario takes place beyond the assumptions made for the BU scenario but below MII scenario trends. Specific assumptions have also to be made in terms of changes in LUTs, including a major increase in irrigated land (larger than in the BU and MII scenarios).

II profile:

Target yields: increase of 4 %/year
Management levels: "Green revolution" solutions, as described above and in the narrative
Management level transitions: from current to II
Target irrigated area expansion: increase of 7-9 % /year
Target rainfed area expansion: increase of 2 %/year
Relations between crop and livestock systems: higher degree of integration between crop and livestock systems. Decrease in grazing cattle number but increase in sedentary draught and fattened cattle and in small ruminants.
Other indicators: higher (than MII, BU) environmental impacts and farming costs related to the use of inputs and irrigation
Sources: based on AGRA (2014), Blein et al. (2008), Zougmoré et al. (2015), Wiggins (2014).

4.8 Moderate input intensification (MII)

The underlying assumption here is the adoption of agricultural technologies with a focus on moderate input intensification[33]. We establish MII yield trends (lower than II trends) based on relevant literature. Expansion of rainfed cultivated land outlined in this scenario takes place beyond the BU and II scenario trends. We also assume specific trends in the expansion of irrigated land (which is larger than in the BU but smaller than in the II scenario). The main difference will be however the technological shift towards moderate input intensification.

MII profile:

Target yields: increase of 2.5 %/year
Management levels: "moderate input intensification", "moderate input intensification" and "smart agriculture" solutions, as described above and in the narrative
Management level transitions: from current to MII
Target irrigated area expansion: increase of 3.5 to 5.5 %/year
Target rainfed area expansion: increase of 2 .5%/year
Other indicators: lower (than II, BU) environmental impacts, lower input costs but higher labour costs

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[32] See for instance Schlenker and Lobell (2010).

[33] e.g. use of improved varieties which are drought tolerant and have lower requirements in terms of nutrients, micro-dosing integrated soil fertility management (integration with livestock), agroecology, agroforestry, systems of crop intensification, integrated pest management, minimum tillage systems, and (water) conservation agriculture.

Relations between crop and livestock systems: highest degree of integration between crop and livestock systems, e.g. livestock lending management, common social organization for water, pastures and soil fertility management with positive effects on rangeland productivity and yield levels.
Sources: based on AGRA (2014), Blein et al. (2008), Zougmoré et al. (2015), Wiggins (2014).

4.9 Extensification (EX)

In this scenario production growth is based on a remarkable expansion of cultivated land, much higher than what is assumed for BU as well as MII and II scenarios. On the opposite the increase in irrigated areas is limited. Further, the assumption is that yields and management levels are as in the baseline situation, i.e. without improvements over the recent technological trends.

EX profile:

Target yields: increase of 0.5 %/year
Management levels: as in the baseline situation, with no further technological improvements
Management level transitions: from current to MII
Target irrigated area expansion: increase of 3.8 %/year
Target rainfed area expansion: increase of 0.75 to 0.9 %/year
Relations between crop and livestock systems: lowest degree of integration between crop and livestock systems. More conflicts with sedentary farmers owing to competition for water and pasture resources.
Other indicators: higher environmental impacts related to land clearing; otherwise as for the baseline.
Sources: based on AGRA (2014), Blein et al. (2008), Zougmoré et al. (2015), Wiggins (2014).

Table 10 Targets used in the modelling and main assumptions in the scenario narratives

Scenario	**Targets used in the modelling**			
	yields (%/year)	**rainfed area expansion (%/year of arable land)**	**irrigated area expansion (%/year)**	**remarks and references**
Baseline*	0.5 %	1- 1.5 %	1 %	Based on AGRA (2014); Blein et al. (2008); FAOSTAT statistics from 2000 to 2011.
BU	0.75%	1.75%	1.2 to 1.5 %	Based on FAOSTAT, AGRA (2014); Wiggins (2014)
II	4%	2 %	7 to 9 %	Based on AGRA (2014, Blein et al. (2008 ; Zougmoré et al. (2015: Wiggins (2014)
MII	2.5%	2.5%	3.5 to 5.5%	Based on AGRA (2014); Blein et al. (2008); Zougmoré et al. (2015)
EX	0.5%	3.8%	0.75 to 0.9%	Based on AGRA (2014); Blein et al. (2008); Wiggins (2014)

* Figures in the baseline scenario are only used as reference, and not as input in the modeling.

Source: Own elaboration, specific references indicated in table.

4.10 Calculation of NPP demand

4.10.1 Calculation of gridded NPP demand and shares

NPP or biomass demand estimate is mainly based on data at country level on food production (plant and animal products), feed use, firewood and charcoal production as well as on biomass burned in the process of land clearing. These were obtained from FAOSTAT. The most recent year for which complete data on all these categories were available was 2012: this year was taken as the reference year. As far as Sudan was concerned, the data were only available for the whole of that country, i.e. including the country South Sudan that seceded from it in 2012.

In turn, spatially explicit population data for the countries involved are sourced from SEDAC - CIESIN [34]. These included detailed population observed data for the year 2000 and data on urban extent for the same year as well as population projections for the years 2010 and 2015. From the website of the UN Department of Economic and Social Affairs (UN DESA 2015) expected population growth rates were obtained – for the country population as a whole as well as for urban population. Finally a shapefile was obtained delineating borders of the countries involved with associated geographic references.

The data on food, feed, fuel and burned biomass is gathered to specific factors to convert volumes of all these different products into quantities of carbon. The factors were retrieved from literature, mostly following the references already provided by Abdi et al. (2014). Scripts were developed to sum the carbon quantities per country, divided over the shares food, feed, fuel and burned biomass. A grid of cells was defined with a size of $^1/_{12}$ th of a degree – both for latitude and for longitude (aligned to the one used for the NPP supply estimates). The data on population and urban extent were aggregated to new raster layers that coincide with the chosen grid. The same was done with the projected population data for 2010 and 2015 and a weighted average was calculated to estimate a projection for population in 2012. The data on the urban extent for 2000 were used to produce 2 raster, representing the percentages of urban and rural area in each grid cell.

The aim was to use national production figures on food, feed, fuel and burned biomass as proxy figures for local consumption and to account – as part of this process – for differences in rural and urban consumption. Hence we set out to estimate which fraction of the population projected for 2012 should be considered urban and which fraction as rural. In order to assess how urban and rural populations in each cell could develop alongside each other, the data from cells with at least some urban area were studied. A simple method was developed to model urbanisation that only takes population pressure into account. A more sophisticated method would have gone beyond the scope of the project. These were the variables studied:

- normal population densities: in terms of people per square kilometers;

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[34] Gridded Population of the World, Version 3 (GPWv3) http://sedac.ciesin.columbia.edu/data/set/gpw-v3-population-density-future-estimates

- linear population densities: people per square kilometer, as introduced by Marshall (2007).

In this case, the concept of linear population density (LPD) was applied to the populations of urban grid cells. The LPD data were studied per country. Good statistical relationships were found between the LPD and the total population of grid cells for most countries. We assumed that these relationships would not change over time. Marshall (2007) presents support for this assumption.

Normal population density (or NPD) was studied especially for rural areas and a pattern was found but not so clear as for LPD in urban areas. Nevertheless it was assumed that NPD in the rural area of a cell has a linear relationship with total the total population, i.e. an increase over time of the total population is assumed to lead to a less than proportional increase in LPD.

With the assumed relationships between urban and rural population and their living areas, we obtained a simple urbanisation model that could be applied to a grid cell, i.e. in order to simulate how the growth of the total population is distributed over a growing urban area and a shrinking rural area. Of course a few other assumptions were introduced, e.g. for urban areas where population is projected to decrease. We refined our simple urbanisation model with a possible transition for a nearby rural cell to become partially urban. We used our model to predict the situation for 2012 and 2015 for each cell, allowing for different values for the search radius to be applied in the different countries. We expected to arrive at national figures for the urban fraction of the population being greater than – or at least equal to – the urban fraction in 2000. It appeared that it was not possible to exactly reach those minimal target fractions – esp. not for Niger, Chad and Sudan. Anyway, with extreme values for the model parameters for these countries, the target fractions were almost reached[35].

The spatially explicit population projection for 2012 was used to estimate the NPP demand in each of the grid cells, and consequently, on a per-capita basis. This was done by apportioning the total demand for each country over its grid cells, i.e. proportionally to the population of those grid cells. The same allocation was done for each demand category, i.e. food, feed, fuel and burned biomass.

The resulting demand shares for the year 2015 served as a basis for projections to the future. The UN DESA population projections to the years 2015 and 2050 were taken as reference and population increase rates calculated accordingly at country level. First the population was projected for 2030 and then again for 2050 on the basis of the result obtained for 2030. The assumption was made that in each country the total demand and the relative shares per person would remain the same between 2012 and 2050. Thus it became straightforward - based on the obtained population projection for 2050 - to arrive at a spatially explicit projection for the carbon demand and of the relative shares for the year 2050.

It was not possible, at this stage of the work, to apply different population growth rates for rural and urban areas as worked out for the year 2015. Therefore, it was also not possible to eventually apply different per capita consumptions /dietary patterns among rural and urban populations, as suggested in Abdi et al.(2014). The relevance of differences between the rural and urban consumption patterns is discussed later in this paragraph.

Agricultural products exports and imports (and therefore imported and exported NPP, as in Erb et al. (2009) were included in the analysis although not in the spatialisation of the

[35] Such results may cast doubts over the population projections for 2010 and 2015 from CIESIN – e.g. as far as the spatial variability of these projections is concerned.

demand. As done for the estimate of the NPP demand, FAOSTAT figures were extracted for a number of import and export quantities (grains, flour, livestock products, live animals, etc.), converted to C quantities and aggregated at national level and analyzed side by side with the "domestically" produced agricultural products, used as a proxy for NPP demand . This aspect is elaborated further in the next sections.

4.10.2 Population projections

As indicated in the previous section, for the projection of population to the year 2050 the UN DESA projections (under the medium variant) from the World Population Prospects were used as the reference.

A number of studies (e.g. (Gerland, Raftery et al. 2014)) point to limitations in the UN projections elaborated in the past, in the light of assumptions such as the recent slowdown in fertility rates and the decline in the ratio of working age people to older people. According to the authors above the mentioned assumptions have an impact which goes beyond even the UN high variant, projections, and this holds especially for Africa. As a consequence, the population is unlikely to stop growing this century as assumed in the previous projections.

However the latest UN DESA (2015) projections from the 2015 revision of the World Population Prospects, which is the source used in our study, do take into consideration a number of the mentioned assumptions such as the higher than expected fertility rates and will be used in the modelling.

4.10.3 Urban vs. rural consumption patterns

The cited study by Abdi et al. (2014) indicates that a provision was made for different consumption patterns in rural and urban areas. However, the methodology used in accounting for such differences is not fully documented, if not for the identification of urban and rural areas. Apart from the difficulties in translating the different consumption patterns in our spatially explicit model, the relative importance of rural/urban patterns versus other factors such as, for instance, income is questioned by a number of authors (Depetris Chauvin, Mulangu et al. 2012; Bricas and Tchamda 2015).

Depetris Chauvin et al. (2012) for instance, investigate food production and consumption trends in Sub-Saharan Africa. They conclude that there are more important differences when looking across different levels of livelihood and gender groups and hence, income levels, than when comparing urban and rural households. On the one hand the growing incidence of urban poor is affecting the overall purchasing power of households in the urban context. On the other hand, emerging non farming households are changing per-capita consumption and dietary patterns of rural households. This is not to underestimate differences in the disposable income for food between urban and rural areas, as observed for instance by Tafere and Worku (2012) in respect to animal products. However it appears difficult to differentiate between rural and urban incomes in the context of the present study, especially when attempting to model this pattern in space. In the scenario narratives the effect on consumptions and dietary patters in relation to the assumptions made on income/GDP growth will be discussed anyhow.

4.10.4 Biomass trade flows

As mentioned, Abdi et al. (2014) use FAOSTAT production figures as a proxy for NPP demand. This is under the assumption that most of the food produced in the region is consumed domestically and trade flows are relatively small.

In this respect the already cited study by Erb et al. (2009), covering the entire Africa, and the one by Haberl et al. (2007), focusing on SSA, do suggest that the weight of the net trade (imports minus exports) is negligible when compared with other world regions.

Given the different geographic extent of this study a specific analysis of the traded agricultural production flows for the Sahelian countries was undertaken. We used FAOSTAT trade data in order to achieve the maximum possible consistency with production data, although limiting our focus to the food and animal feed shares.[36] The FAOSTAT trade data (food and feed items) for the most recently available year (2012) were converted into dry matter and further to carbon content, which is equivalent to NPP. The same conversion factors adopted for the NPP demand calculations were used as well as additional ones when needed. All relevant food items, i.e. crop products (both in terms of grains and processed products such as flour) as well as animal products and live animals were included, taking special care to avoid double counting. The results for the food share are reported in Table 11.

Differently than what was concluded in previous works, it appears that the trade flows for the Sahelian countries, although possibly negligible when seen in relation to other areas in the world, are not marginal when compared to their domestic production. When looking specifically at the food component the net flow (in all countries imports exceed exports) sum to a total of around 10.4 M tons of C, which is on average around 13% of the domestic production. As it can be expected figures vary depending on the country, with Nigeria accounting for most of it in absolute terms, while countries like Gambia, Mauritania and Senegal having the highest incidence in percentage. Figures for South Sudan are not available for 2012. In order to also include the import/export share for South Sudan, figures for the year 2011 referring to former Sudan for 2011 were used instead.

When also accounting for the feed component, the net flow is equal to 11.5 M tons of C and the ratio of net trade flow over the domestic production is down to 8%. This reflects the importance of livestock exports for some countries (mainly Sudan, Niger, Mali and Burkina Faso) and livestock products to a lesser extent (Senegal).

[36] The amount of traded goods related to fuel appears to be negligible for the Sahelian countries, although informal flows are most likely not fully captured by the official statistics.

Table 11 Food net trade flows and domestic production (in tons of C)

AreaCode	Country	Domestic production	Exports	Imports	Net flow (1)	Balance (2)	Net flow/dom. production (3)
39	Chad	3,801,355	10,244	143,277	(133,034)	3,934,388	3%
75	Gambia	319,056	5,301	212,502	(207,201)	526,257	65%
133	Mali	7,307,274	76,980	611,110	(534,130)	7,841,404	7%
136	Mauritania	244,150	67	132,403	(132,336)	376,486	54%
158	Niger	6,105,119	52,885	422,331	(369,446)	6,474,565	6%
159	Nigeria	47,754,630	122,275	6,355,732	(6,233,457)	53,988,086	13%
178	Eritrea	269,640	-	140,819	(140,819)	410,459	52%
195	Senegal	2,405,129	49,221	663,859	(614,637)	3,019,767	26%
233	Burkina Faso	6,023,241	156,226	531,190	(374,963)	6,398,204	6%
206	Sudan (4)	5,784,605	115,654	1,817,479	(1,701,825)	7,486,430	29%
TOTAL		80,014,199	588,852	11,030,701	(10,441,848)	90,456,048	13%

(1) Exports minus imports

(2) Domestic production minus net flow

(3) in %

(4) 2011 figures are used since for the year 2012 data from South Sudan are not available

Reference year: 2012

Expressed in tons of carbon

Source: Own elaboration based on data from 2012 by FAOSTAT (2015)

The calculation of the net trade flows is especially important when interpreting the results of the HANPP.

In the case of the baseline situation the NPP demand and supply for food (the latter inclusive of the current net trade flow, i.e. the net imports) should, at least approximately, balance out. In other words the domestic production for food plus the net exports should by and large match the total demand.

However, as shown in the next paragraph, the estimated demand still exceeds the supply by around 15%. There are a number of reasons for this mostly related to inaccuracies in the estimates of either the demand or the supply. Shortcomings in the statistical systems of the countries concerned may lead to over-reporting of domestic food production statistics[37] as well as underreporting of food trade statistics (due to the inability to capture all informal trade flows) and should be taken into consideration. As discussed for instance in Carletto et al. (2013), the "routine data system" which are the data collection systems in place in most countries in SSA, may lead to systematic biases. When government extension workers are the main data collectors, there are risks of biases in crop production estimates to be on the higher side, consistently with objectives of growth in agricultural productivity.

The net trade flows figures were finally included in the calculation of the aggregated HANPP and are shown in the aggregated results of the scenarios. Given the difficulties in objectively apportioning their contribution in space however, these were not added to the spatialisation procedure of the domestic production described earlier in this paragraph.

[37] As discussed for instance in Carletto et al. 2013, the "routine data system" which are the data collection systems in place in most countries in SSA, may lead to systematic biases. When government extension workers are the main data collectors, one can expect that biases in crop production estimates will be on the higher side, consistently with objectives of growth in agricultural productivity.

4.10.5 Consideration of the livestock component

In order to evaluate possible "hot spots" or "hope spots" between livestock raising and cropping as discussed in 3.4, the Gridded Livestock of the World (GLW version 2.01, see appendices) and specifically the layer for cattle density was used.[38]

The cattle densities originally expressed as animals counts per square kilometer, were reclassified to retain only areas with densities > 50 animals per square kilometer, regarded as those where conflicts in the new cropped areas would most likely occur.

The outcome was further superimposed to the maps of the expansion areas (irrigated and rainfed) for the different scenarios. This procedure allowed singling out a specific set of potential "hot spots" or "hope spots", also depending on the scenario assumptions, as well as the additional areas candidate for expansion (of both irrigated and rainfed cropland) which are also subject to encroachment of cattle (although with lower densities). Examples of "hot spots" and "hope spots" areas are presented in the paragraphs on the scenario outcomes and full maps are given in the appendixes.

5 Scenarios Outcomes

The outcomes of the scenario modelling as described in the paragraph on model implementation consist in a number of GIS layers, one for each of the scenarios. The layers contain the following information (for each modelling unit or cell):

- the non-crop and crop LUTs resulting from the allocation process, with the associated area share and the type of transition (e.g. from non-cultivated to rainfed, rainfed to irrigated, etc.). In the appendices, maps representing the final transitions for two example scenarios are given;
- NPP supply values, calculated as total and per share: this includes projected values for the food and fibre components only, and the current ones for the remaining feed and fuel shares for the year 2050;
- NPP projected demand values also divided in food, feed, fuel shares, and additionally, biomass burned;
- HANPP calculated as difference (or ratio) between NPP supply and demand.

The outcomes above are reported for specific aggregation units (AEZ, administrative units).

A map of cells representing "hot spots" and "hope spots" is generated as well, and representative locations are analyzed as part of the scenario narratives: see appendices.

5.1 Aggregated results

When considering the whole study area, Table 12 provides a number of reference data as well as the final aggregated outcomes for the baseline and the different scenarios. NPP is expressed in total tons of C. The current HANPP, based on the data for the baseline situation and expressed as ratio (in %) between total NPP demand over total NPP supply, is equal to 29%. This considers the shares of food, feed and fuel but excludes from the calculation from

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[38] The selection of cattle population only was based on its importance in terms of the specific interactions between livestock and cropping components this study intends to focus on.

the demand of the biomass burned.[39] As it has been discussed in previously, net trade flows of food and feed are also included.

In terms of per capita NPP demand this corresponds to 1 ton of C per person/year all shares included. It has been assumed that this per capita figure remains unchanged in the projection to the year 2050. The per capita NPP supply for the baseline is 3.4 tons/person/year.

When looking at the scenario results, with NPP values projected to the year 2050, the HANPP ratios are as follows (Figure 2):

- BU scenario: 78%;
- II scenario: 75%;
- MII scenario: 78%;
- EX scenario: 88%.

The per capita NPP supply for all shares ranges from 1.33 tons/person/year for the II scenario to 1.14 tons/person/year for the EX scenario.

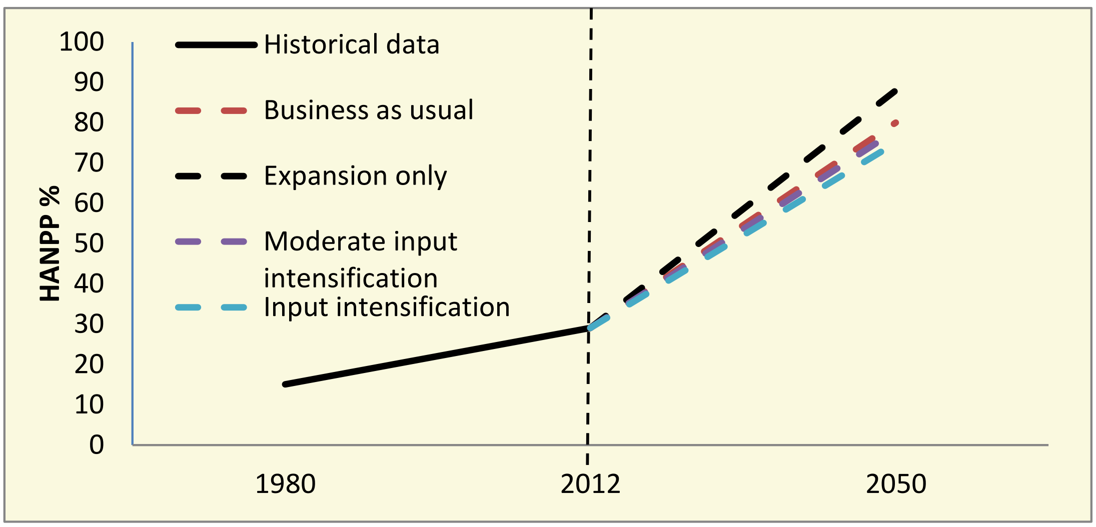


Figure 2 Recorded (solid line) and projected (dashed lines) HANPP in 11 Sahel countries (1980-2050), according to agricultural scenarios and current individual dietary preferences and consumption levels. (Source: Own estimates and elaboration)

For the food share alone, the picture is different, with the HANPP ranging from 115% in the baseline, to 165% and 199 % respectively for the II and MII scenarios, and 272% and 282% for the BU and EX scenarios. The per capita NPP supply for food in the baseline situation is 0.2 tons/person/year. When considering the 2050 scenarios it decreases to 0.17 for the II scenario, to 0.14 in the MII scenario and to 0.10 in the remaining BU and EX scenarios. If we add the two components of food and feed (the sum of the two represent the what can be regarded as directly relevant in terms of "food security"), the per capita NPP supply is 0.94 tons/person/year of C for the baseline situation as well as for the II scenario (despite the doubling of the population), and proportionally less for the others scenarios (0.9 for MII, 0.88 for BU and 0.79 for EX).

As a first element for a broader discussion, it is worth noticing that the two scenarios based on the more remarkable technological improvements in agriculture (II, MII) do attain the best results in terms of the food share, although this is not sufficient to compensate for a

[39] The procedure indicated by Abdi et al. (2014) includes this component in the calculation of the demand share. However a more thorough analysis of the appropriateness of the input data used and especially of the projection methods to the year 2050 would be required, which could not be carried out in this study.

demand which is more than doubling over the same period. The other scenarios and particularly the EX scenario, lead to worse coverage of the food demand. As far as the feed and fuel components, the EX scenario leads to the highest HANPP (hence, the highest appropriation levels for both shares) due to the sizable expansion of rainfed areas to the detriment of natural vegetation. Always in relation to the larger expanded cropland (irrigated and rainfed), the MII and then the II scenarios have higher appropriation rates than the BU scenario. Even though differing in their spatial extent and the methodologies used, results from a number of key studies identified in the literature review (see section 1.2), allow some comparisons. Ardö (2015) for instance, estimates for the year 2030 that the human-appropriated NPP will range from 67% in the Sahel region to 200% or more in some "desert states".[40]

All scenarios were also run under the assumption of no climate change, i.e. assuming only the effect of technological trends on crop yields (Figure 3). Results (always including net trade flows) are also reported in Table 12. With regards to the food share the differences in the scenario outcomes are remarkable. This is especially the case of the II scenario where the HANPP food improves from 165% to 93%, also due to a better performance of high yielding varieties. In the MII scenario the HANPP food improves from 199% to 134%; In the BU scenario the improvement is from 272% to 242% while in the EX scenario from 282% to 254%. HANPP for the feed and fuel shares are unchanged, given the underlying assumptions on the effect of CC on the two components.

The results regarding food could be translated into self-sufficiency as extent to which a country can satisfy its food needs from its own domestic production" (FAO 1999). As such, none of the scenarios are expected to reach such a goal.

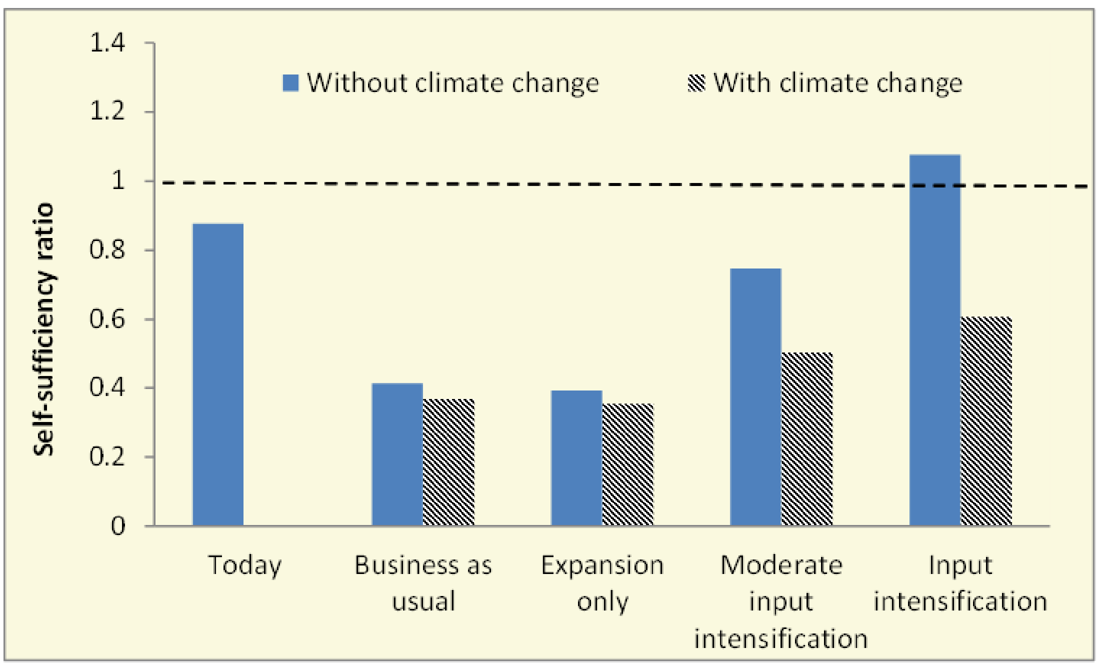


Figure 3 Self-sufficiency ratio (self-sufficient when ≥1, relies on imports if ≤1), depending on the agriculture scenario with and without the estimated effect of climate change by 2050. (Source: Own estimates and elaboration)

[40] In the study cited the HANPP is also calculated as the fraction between consumed NPP/produced NPP (for food, feed and fibre), with the consumption calculated as an average of 2 t NPP per capita and the supply estimated in a range from 3 to 1 t per capita/year.

5.2 Results by country and AEZ

The aggregated results presented in the previous section have been further tabulated based on different reporting units, and namely per country and by agro-ecological zones (derived from the GAEZ database, see appendices for more references). The results of the per country break-down are presented in Table 13. The scenario outcomes show a number of "better-off" countries such as Sudan (based on former Sudan 2010 figures, including both Sudan and South Sudan), Senegal, Gambia, Chad and Nigeria, with total HANPP below 67%. It also shows "worse-off" countries such as Eritrea, Niger and Mauritania, with total HANPP above 180% for the year 2050.

Table 12 Final scenario outcomes (aggregated)

year	2012	2050
Population	281,606,000	697,969,000

NPP demand	tons C		tons C / person	tons C		tons C / person
food	80,014,199	28%	0.3	199,336,359	28%	0.3
feed	153,932,717	54%	0.5	377,093,506	54%	0.5
fuel	50,713,056	18%	0.2	124,177,054	18%	0.2
Total	**284,659,972**	100%	**1.0**	**700,606,919**	100%	**1.0**

NPP supply, trade flows included

	Reference period				Scenarios 2050, with climate change															
					BU				II				MII				EX			
	tons C	%	tons C / person	HANPP (4)	tons C	%	tons C / person	HANPP		%	tons C / person	HANPP		%	tons C / person	HANPP		%	tons C / person	HANPP
food (1)	67,868,428	7.2%	0.2	115%	71,217,358	8.1%	0.10	272%	117,552,178	13.0%	0.17	165%	97,164,708	10.8%	0.14	199%	68,756,278	8.7%	0.10	282%
fiber (2)	1,962,290				2,038,330				3,472,220				2,840,790	0.3%			1,919,780	0.2%		
feed (3)	586,608,505	60.6%	2.1	26%	542,484,155	60.0%	0.78	70%	531,686,315	57.2%	0.76	71%	524,956,745	58.2%	0.75	72%	477,657,335	60.1%	0.68	79%
fuel	310,983,290	32.1%	1.1	16%	288,076,670	31.9%	0.41	43%	276,191,270	29.7%	0.40	45%	276,447,280	30.7%	0.40	45%	245,846,840	31.0%	0.35	51%
Total	967,422,513	100%	3.4	29%	903,816,513	100%	1.29	78%	928,901,983	100%	1.33	75%	901,409,523	100%	1.29	78%	794,180,233	100%	1.14	88%
per capita food + feed			0.94				0.88				0.94				0.90				0.79	

(1) including net trade flow (exports-imports), food component (2012 figures)
(2) summed to the food component for calculating tons of C/person and the HANPP
(3) including net trade flow (exports-imports), feed component (2012 figures)
(4) calculated as ratio between NPP demand and supply, in %

					Scenarios without climate change (5)															
					BU				II				MII				EX			
	tons C	%	tons C / person	HANPP (4)	tons C	%	tons C / person	HANPP		%	tons C / person	HANPP		%	tons C / person	HANPP		%	tons C / person	HANPP
food					80,104,788	9.0%	0.12	242%	211,915,488	21.1%	0.31	93%	145,981,168	15.7%	0.21	134%	76,640,738	9.8%	0.11	254%
fiber					2,315,680				3,523,970				2,851,330				1,930,270			
feed					542,484,155	59.4%	0.78	70%	531,686,315	52.0%	0.76	71%	524,956,745	55.2%	0.75	72%	477,657,335	59.6%	0.68	79%
fuel					288,076,670	31.6%	0.41	43%	276,191,270	27.0%	0.40	45%	276,447,280	29.1%	0.40	45%	245,846,840	30.7%	0.35	51%
Total					912,981,293	100%	1.31	77%	1,023,317,043	100%	1.47	68%	950,236,523	100%	1.36	74%	802,075,183	100%	1.15	87%
per capita food + feed			-				0.90				1.07				0.97				0.80	

(5) feed and fuel components are unchanged, trade flows included

Source: Own estimates and elaboration

Table 13 Scenario outcomes by country

HANPP per country

calculated as ratio between NPP demand and supply, in %

Burkina Faso

Scenarios 2050

Shares	Baseline	BU	II	MII	EX
food (1)	186%	427%	252%	290%	410%
feed	37%	113%	117%	111%	130%
fuel	45%	144%	154%	172%	173%
Total	**50%**	**150%**	**146%**	**147%**	**171%**

Chad

Scenarios 2050

Shares	Baseline	BU	II	MII	EX
food	244%	587%	301%	359%	575%
feed	20%	56%	62%	55%	58%
fuel	12%	33%	40%	41%	38%
Total	**22%**	**61%**	**69%**	**64%**	**65%**

Eritrea

Scenarios 2050

Shares	Baseline	BU	II	MII	EX
food	70%	128%	85%	101%	137%
feed	125%	297%	301%	287%	351%
fuel	15%	33%	45%	45%	69%
Total	**62%**	**141%**	**156%**	**157%**	**214%**

Gambia

Scenarios 2050

Shares	Baseline	BU	II	MII	EX
food	63%	125%	91%	103%	123%
feed	16%	34%	34%	48%	39%
fuel	38%	81%	84%	82%	101%
Total	**26%**	**56%**	**54%**	**67%**	**64%**

Mali

Scenarios 2050

Shares	Baseline	BU	II	MII	EX
food	295%	790%	483%	582%	813%
feed	41%	118%	120%	126%	120%
fuel	14%	41%	42%	42%	42%
Total	**45%**	**131%**	**129%**	**135%**	**134%**

Mauritania

Scenarios 2050

Shares	Baseline	BU	II	MII	EX
food	48%	102%	80%	89%	104%
feed	120%	244%	246%	250%	245%
fuel	38%	77%	84%	77%	79%
Total	**90%**	**183%**	**185%**	**184%**	**186%**

Niger

Scenarios 2050

Shares	Baseline	BU	II	MII	EX
food	366%	1388%	863%	1038%	1440%
feed	109%	439%	444%	571%	442%
fuel	92%	375%	382%	382%	381%
Total	**127%**	**511%**	**490%**	**589%**	**518%**

Nigeria

Scenarios 2050

Shares	Baseline	BU	II	MII	EX
food	96%	215%	131%	160%	223%
feed	19%	45%	46%	54%	45%
fuel	24%	55%	57%	56%	57%
Total	**32%**	**75%**	**69%**	**78%**	**76%**

Senegal

Scenarios 2050

Shares	Baseline	BU	II	MII	EX
food	94%	175%	105%	126%	168%
feed	26%	52%	57%	63%	54%
fuel	27%	53%	65%	58%	56%
Total	**32%**	**63%**	**66%**	**71%**	**65%**

Sudan (Sudan + South Sudan)

Scenarios 2050

Shares	Baseline	BU	II	MII	EX
food	71%	135%	83%	99%	137%
feed	23%	54%	54%	50%	55%
fuel	6%	15%	15%	15%	16%
Total	**18%**	**42%**	**42%**	**40%**	**44%**

(1) includes fibre and net trade flow (exports-imports) for the food/feed components(2012 figures)

Source: Own estimates and elaboration

The scenario outcomes were further calculated excluding Nigeria, based on the reasons indicated in Paragraph 3.1. Results are given in Table 14.

The model run results excluding Nigeria indicate a worsening situation for all scenarios. The overall HANPP in the II scenario for instance, worsens from 75% to 80% (for the food share from 165% to 243%). In the EX scenario the total HANPP evolves from 88% to 97% (the HANPP food from 282% to 420%).

Table 14 Scenario outcomes excluding Nigeria

Scenarios 2050, excluding Nigeria

	BU			II			MII			EX		
	tons C	%	HANPP	tons C	%	HANPP	tons C	%	HANPP	tons C	%	HANPP
food (1)	19,603,497	3.8%	409%	33,021,527	6.4%	243%	27,741,397	4.8%	290%	19,183,397	4.1%	420%
fiber (2)	2,020,740			3,447,590			2,816,250	0.5%		1,903,230	0.4%	
feed (3)	367,256,085	64.2%	81%	358,883,635	63.0%	83%	378,284,515	64.9%	79%	302,778,135	64.7%	99%
fuel	183,527,180	32.1%	36%	174,730,190	30.6%	38%	174,085,300	29.9%	38%	143,966,320	30.8%	46%
Total	572,407,502	100%	79%	570,082,942	100%	80%	582,927,462	100%	78%	467,831,082	100%	97%

(1) including net trade flow (exports-imports), food component (2012 figures)
(2) summed to the food component for calculating tons of C/person and the HANPP
(3) including net trade flow (exports-imports), feed component (2012 figures)
(4) calculated as ratio between NPP demand and supply, in %

Source: Own estimates and elaboration

A further break down of the NPP supply is presented by agro-ecological zones (AEZ). AEZs are those based on the GAEZ FAO/IIASA methodology (see appendices for more details). Results are shown in Table 15and reported in percentages, to indicate the relative contribution of each AEZ as well as its relative importance in terms of area.

Figures refer to the baseline and to the BU and II scenarios as examples.

To better illustrate the level of HANPP in terms of agro-ecological zones, the limits of the same AEZs have been superimposed to the HANPP maps. An example with reference always to the II scenario is given in Figure 2.

Table 15 Breakdown of NPP supply per AEZ

AEZ	Class	area	Baseline NPPSfood	NPPSfiber	NPPSfeed	NPPSfuel
211	Subtropic - warm / arid	3.9%	0.0%	0.0%	0.0%	0.0%
221	Subtropic - warm / semiarid	1.4%	0.0%	0.0%	0.0%	0.0%
311	Tropic - warm / arid	50.7%	1.7%	0.1%	1.7%	1.7%
312	Tropic - warm / semiarid	29.3%	27.0%	67.1%	42.2%	30.1%
313	Tropic - warm / subhumid	12.2%	60.3%	32.7%	52.4%	58.9%
314	Tropic - warm / humid	0.6%	8.8%	0.0%	1.6%	5.2%
321	Tropic - cool / arid	1.2%	0.1%	0.0%	0.1%	0.2%
322	Tropic - cool / semiarid	0.4%	0.3%	0.0%	0.4%	0.8%
323	Tropic - cool / subhumid	0.3%	1.6%	0.0%	1.6%	2.8%
324	Tropic - cool / humid	0.02%	0.12%	0.00%	0.10%	0.28%
		100%	100%	100%	100%	100%

AEZ	Class	area	BU NPPSfood	BU NPPSfiber	BU NPPSfeed	BU NPPSfuel	II NPPSfood	II NPPSfiber	II NPPSfeed	II NPPSfuel
211	Subtropic - warm / arid	3.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
221	Subtropic - warm / semiarid	1.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
311	Tropic - warm / arid	50.7%	2.1%	0.1%	1.8%	1.8%	1.5%	0.1%	1.8%	1.7%
312	Tropic - warm / semiarid	29.3%	27.7%	67.0%	42.3%	29.6%	27.6%	67.4%	41.2%	28.7%
313	Tropic - warm / subhumid	12.2%	59.4%	32.8%	51.9%	58.7%	60.0%	32.4%	52.9%	59.5%
314	Tropic - warm / humid	0.6%	8.6%	0.0%	1.7%	5.6%	8.8%	0.0%	1.8%	5.8%
321	Tropic - cool / arid	1.2%	0.1%	0.0%	0.1%	0.2%	0.1%	0.0%	0.1%	0.2%
322	Tropic - cool / semiarid	0.4%	0.4%	0.1%	0.4%	0.8%	0.3%	0.0%	0.4%	0.6%
323	Tropic - cool / subhumid	0.3%	1.5%	0.0%	1.7%	2.9%	1.6%	0.0%	1.7%	3.0%
324	Tropic - cool / humid	0.02%	0.12%	0.00%	0.11%	0.30%	0.12%	0.00%	0.11%	0.31%
		100%	100%	100%	100%	100%	100%	100%	100%	100%

Source: Own estimates and elaboration

5.3 Maps of HANPP, "hot spots" and "hope spots"

Maps comparing NPP demand and supply were generated for each scenario and share (food, feed, and fuel) as well as for the baseline. These are equivalent to maps on HANPP, although they differ in the way HANPP data are presented with respect to the aggregate figures (in the latter case through the ratio between NPP demand and supply). The reason is related to the occurrence of areas where the NPP supply component is null, but where at the same time the NPP demand can be extremely high, as it typically occurs in the main urban centers.

Excluding the class that combines areas not evaluated in terms of demand and supply, all other classes were derived based on quantiles and further grouped to indicate, respectively: areas with unfavorable conditions (low demand and no, very low to low supply), areas with favorable conditions (high demand and high supply), "hot spots" (high demand and low supply) and finally "hope spots" (low demand and high supply).

One example of the final maps obtained with reference to the II scenario and the NPP food component is given below, while the complete map set is given in the appendices.

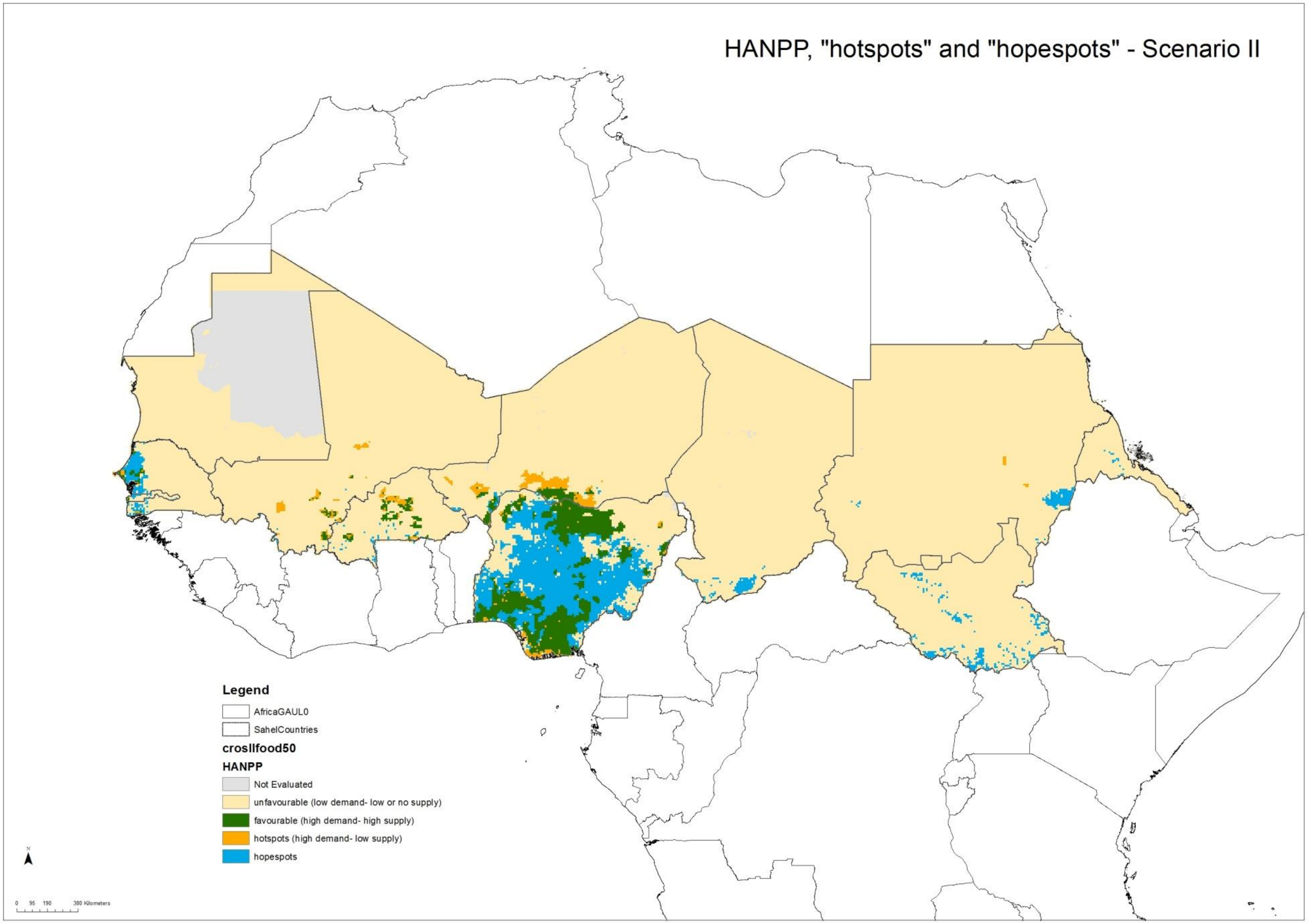


Figure 4 HANPP, "hot spots" and "hope spots", food component, scenario II (Source: Own estimates and elaboration)

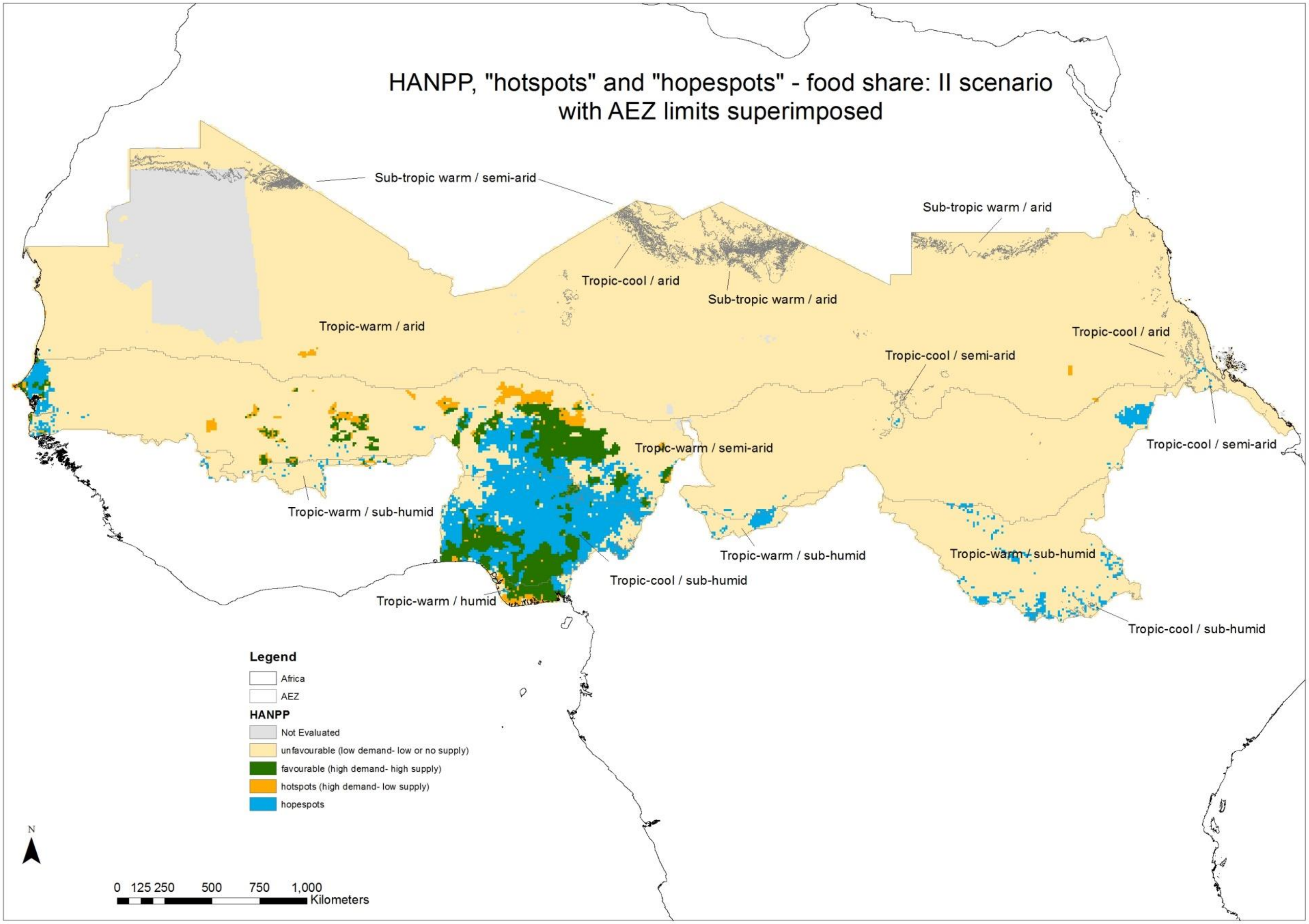


Figure 5 HANPP and AEZs (Source: Own estimates and elaboration)

5.4 Occurrence of “hot spots” and “hope spots” per Land Use Type

“Hot spots” and “Hope spots” were also analyzed in terms of occurrence of crop based Land utilization types or LUTs, as classified in Table 6. Occurrences are reported in Table 16. The most important ones are highlighted in bold.

Table 16 Occurrence of "hot spots" and "hope spots" per LUT

	Scenarios							
	BU		**II**		**MII**		**EX**	
LUT	Hotspots	Hopespots	Hotspots	Hopespots	Hotspots	Hopespots	Hotspots	Hopespots
FIB_H	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
FIB_I	0.2%	0.0%	0.3%	0.0%	0.3%	0.0%	0.2%	0.0%
FIB_LS	0.9%	0.0%	1.4%	0.0%	0.9%	0.0%	0.9%	0.0%
FRUI_H	0.0%	0.2%	0.0%	0.1%	0.0%	0.1%	0.0%	0.2%
FRUI_LS	0.6%	9.3%	0.7%	7.9%	0.7%	8.5%	0.6%	9.4%
LEG_H	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
LEG_LS	12.9%	7.4%	16.3%	12.0%	15.3%	11.0%	12.5%	7.2%
MAIZ_H	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
MAIZ_I	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
MAIZ_LS	0.7%	2.1%	0.9%	3.3%	0.7%	3.2%	0.7%	2.0%
MIL_H	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
MIL_LS	41.9%	5.0%	44.1%	7.0%	41.5%	4.9%	42.1%	5.0%
OILC_H	0.0%	0.3%	0.0%	0.3%	0.0%	0.3%	0.0%	0.4%
OILC_I	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
OILC_LS	0.9%	7.9%	1.2%	6.8%	1.2%	7.3%	0.9%	8.3%
OTHC_LS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
OTHE_H	0.1%	0.2%	0.0%	0.1%	0.1%	0.2%	0.1%	0.2%

OTHE_I	0.1%	0.0%	0.2%	0.0%	0.1%	0.1%	0.1%	0.0%
OTHE_LS	0.3%	0.6%	0.3%	0.5%	0.4%	0.6%	0.3%	0.7%
POIL_H	0.2%	0.0%	0.3%	0.0%	0.3%	0.0%	0.2%	0.0%
POIL_LS	1.2%	4.2%	1.9%	2.7%	1.5%	3.2%	1.2%	4.3%
RICE_I	2.4%	0.3%	2.8%	0.4%	3.1%	0.4%	2.3%	0.3%
RICE_LS	0.5%	4.7%	0.5%	3.4%	0.4%	3.9%	0.5%	4.9%
RTC_H	0.0%	0.1%	0.0%	0.0%	0.0%	0.1%	0.0%	0.1%
RTC_I	0.1%	0.3%	0.0%	0.3%	0.1%	0.3%	0.1%	0.4%
RTC_LS	6.2%	30.9%	9.0%	21.5%	8.3%	24.6%	6.0%	32.0%
SORG_H	0.0%	1.8%	0.0%	2.9%	0.0%	2.5%	0.0%	1.6%
SORG_I	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SORG_LS	29.3%	24.1%	17.3%	30.2%	22.6%	28.4%	30.0%	22.7%
SUGC_I	0.9%	0.0%	1.6%	0.0%	1.3%	0.0%	0.9%	0.0%
SUGC_LS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
VEGE_H	0.3%	0.0%	0.5%	0.0%	0.4%	0.0%	0.3%	0.0%
VEGE_I	0.3%	0.3%	0.5%	0.3%	0.4%	0.3%	0.3%	0.4%
VEGE_LS	0.1%	0.0%	0.2%	0.1%	0.1%	0.1%	0.1%	0.0%
Totals	100.0 %	100.0%	100.0 %	100.0%	100.0 %	100.0%	100.0 %	100.0%

Source: Own estimates and elaboration

5.5 “Hot spots” and “hope spots” in relation to the livestock component

Additional “hot spots” and “hope spots”, specific to the relationship between cropping and livestock systems, have been identified based on the procedure previously described.

The nature of these locations (“hot spots” or “hope spots”) depends on the scenario type. Locations combining high densities of cattle and crop expansion areas under scenarios BU and EX are regarded as “hot spots”. The occurrence of the same conditions is regarded as a “hope spot” in the case of the II and MII scenarios.

The remaining areas candidates for cropland expansion under the different scenarios are mapped representing additional zones of encroachment although occurring in combination with lower cattle densities.

Illustrative maps of specific areas and scenarios with potential livestock "hot spots" and "hope spots" are presented below. Maps covering the entire study areas are presented in annexes.

Figure 4 highlights the "hope spots" in the western part of the study area, including Mali, Burkina Faso and Nigeria. The areas colored in blue indicate where, under the assumptions of the II scenario in this example, positive synergies would apply at territorial level including improved common management of livestock, water and rangeland resources, as well as improved soil fertility management at farm level.

Figure 5 indicates, for the same areas, "hot spots", which are the same intersection areas but under the EX scenario in this example. In this case the low degree of integration between crop and livestock systems is conducive of more conflicts between herders and sedentary farmers, due to increased competition for water and pasture resources.

Figure 6 and Figure 7 refer to the Easter part of the area under study, namely south Sudan and Eritrea, with examples of "hope spots" and "hot spots" identified as described previously.

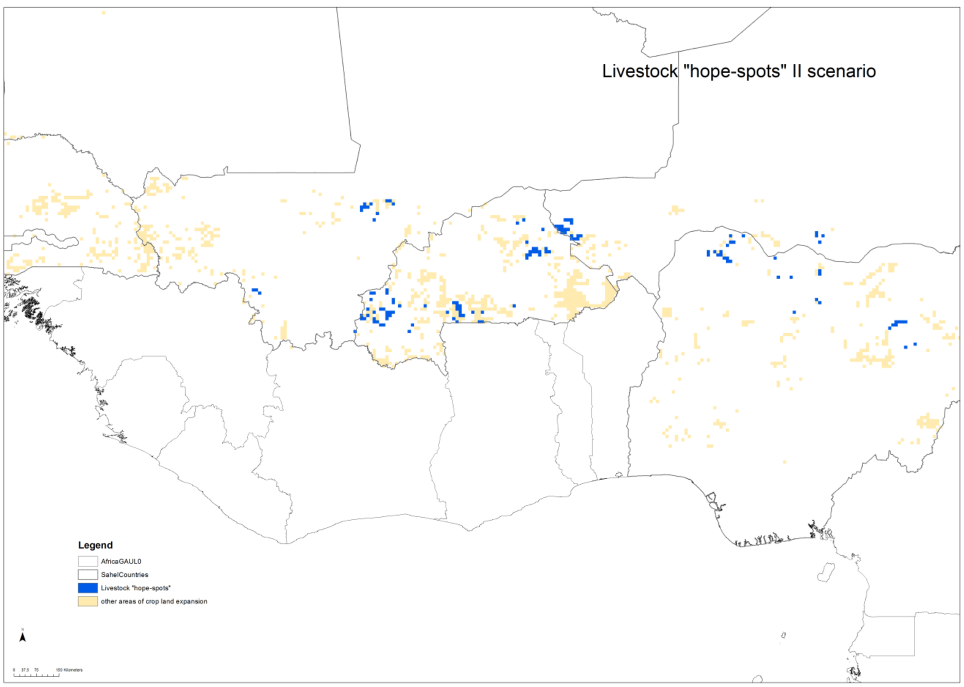


Figure 6. Examples of livestock "hope spots" in the II scenario

Source: Own estimates and elaboration

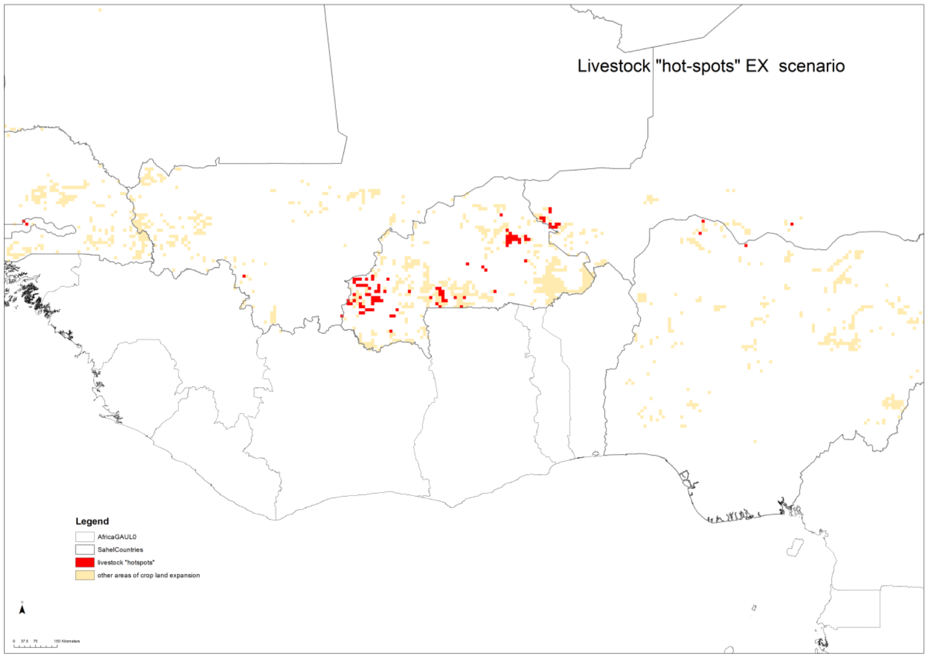


Figure 7. Examples of livestock "hot spots" in the EX scenario

Source: Own estimates and elaboration

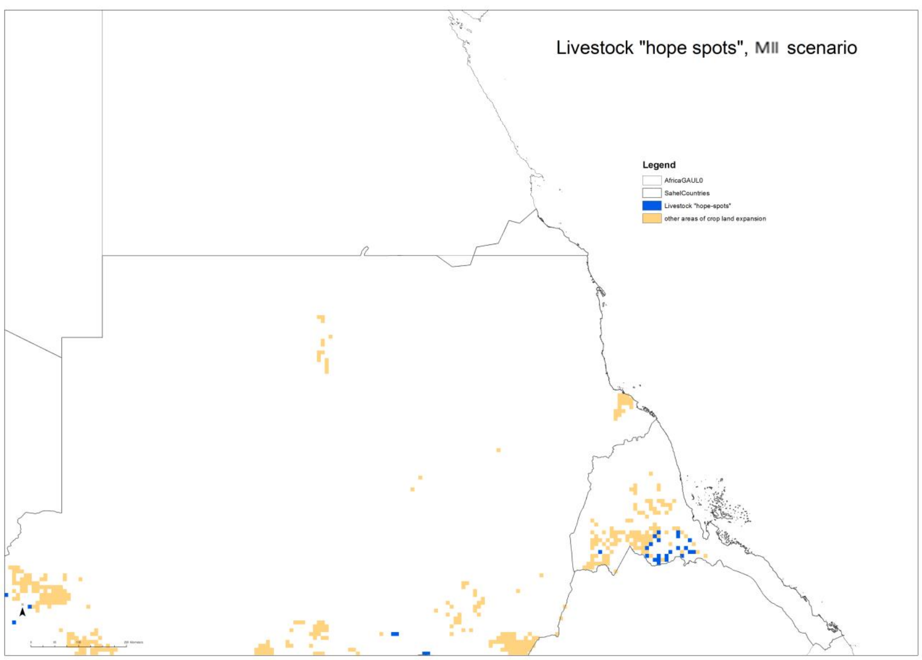


Figure 8. Examples of livestock "hope spots" in the MII scenario

Source: Own estimates and elaboration

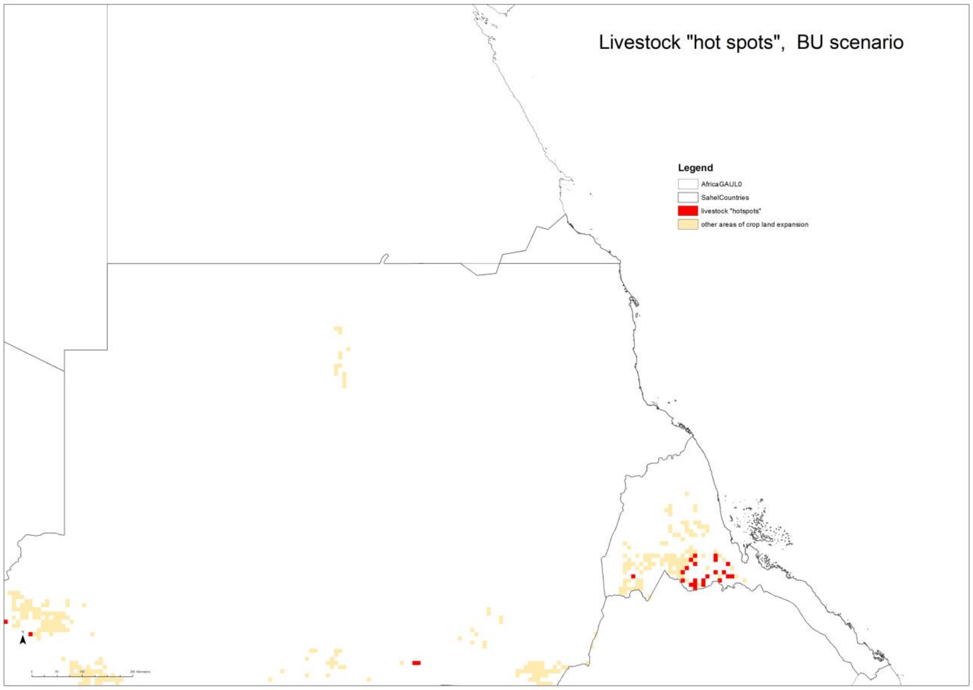


Figure 9. Examples of livestock "hot spots" in the BU scenario

Source: Own estimates and elaboration

6 Scenarios Narratives

Scenarios narratives are defined, with reference to a baseline situation, to support the scenario modelling. Each scenario is described in function of a socioeconomic context (GDP, food, fuel, and feed demand and supply, market integration & trade) and a productive context specifically addressing the agricultural sector (rainfed and irrigated land, LUTs, yields, environmental impact, HANPP outcomes). Assumptions are also made, equally for all scenarios, on the climate context and its effect on the specific scenarios (expected negative impacts, possible adaptation measures).

This section is also intended for analyzing and testing dynamics and linkages between and within the agriculture scenarios. Namely we explore, identify and assess pathways, transitions, changes and tipping points with references to the scenarios as well as through an in-depth analysis of selected “hot spots” and “hope spots”.

6.1 Baseline

The baseline combines:

- 2000-2010 socio-economic trends;
- 2000-2010 productive trends.

Socioeconomic context: over the period considered the context was positive, with mean GDP growth in the order of 3.2%/year. Nevertheless the agricultural sector was not the main beneficiary. Population growth was still high (3%/year), accompanied by urbanisation (FAOSTAT, 2015). The market orientation has been towards an increased regional demand for food and feed, with increasing prices coinciding for instance with the surge in global food prices from 2007 onwards, but also more recent periods of decline in commodity prices (e.g. coinciding with decreasing demand and economic stagnation of the world economy, as in 2014-2015) which in principle favors the increase of food imports (Depetris Chauvoin et al., 2012; FAOSTAT; Jayne et al., 2014).

Productive context: even in presence of high GDP growth (more than 3%/year) and ahead of population growth, the 2007-2009 economic crisis resulted in important socioeconomic impacts given the instability in commodities markets (e.g. decrease in agricultural export products such as cotton, and prices of agricultural inputs and food imports such as fertilizer, oil, cereals and rice doubling and trebling within a few months) (FAOSTAT, 2015; Wiggins, 2014). As a result the Sahel and Western Africa countries are only now recovering from the impacts of this crisis (FAO, 2015). Production increases responded to growth in demand thanks to a slightly higher productivity of land and labour but especially due to an increase in cultivated lands (Blein, Soulé et al. 2008; Wiggins 2014). In fact increases in yields during 2000-2010 remained modest, with a growth rate of 0,5 %/year while new arable land grew at 1-1.5%/year for rainfed cultivation and 1%/year for irrigation (FAOSTAT, 2015). As a result, the increases in regional production lead to qualitative and quantitative improvements in diets. Nevertheless cereals and rice production did not cover regional demands. This is also seen in the balance between NPP food supply and demand (or HANPP supply) calculated in this study. For the period used as the baseline, the estimate is that NPP demand exceeds supply of around 35%. As reported in Table 11, this difference is partially to be ascribed to the net traded flows (as reported by official statistics). When considering food imports minus exports, the HANPP reaches 115%. Other possible reasons are discussed later. Animal production did not stagnate, although growth rates were even lower than for crop production (FAOSTAT, 2015). HANPP for feed is 26% and for fuel 16%. The overall HANPP (food, feed and fuel shares included) is 29%.

Climatic context: there were no major climatic events in the period 2000-2010 such as those experienced in the region during the 1970s and early 1980s when severe droughts hit the Sahelian and Sudano-Sahelian areas, reducing production to virtually nil (Blein, Soulé et al. 2008; Wiggins 2014).

6.2 Scenarios

Business as usual (BU)

The BU scenario combines:

- Stable socioeconomic context;
- Unfavorable productive context;
- Unfavorable climate context.

Socioeconomic context: GDP growth rate in this scenario still high, from 3 to 3.5 %/year. Population growth is still in the order of 3%/year, and expected to more than double by the year 2050. This growth is accompanied by increasing urbanization (FAOSTAT, 2015). Therefore, demands for food, fuel and feed grow in particular in urban areas. Given the widening gap between NPP food demand and supply one can expect an increase in imports and prices over the scenario horizon; although as seen previously, the prices for a number of food commodities may be heavily influenced by decreasing demand and economic stagnation of the global economy. Market integration, even if with some improvements, is still unfavorable.

Productive context: production increases, responding to the growth in demand, are mostly due to increases in cultivated areas and to a slight increase in the productivity of farming systems (Blein, Soulé et al. 2008; Wiggins 2014). Increases in yields are assumed to be in the order of 0,75%/year, mainly due improvements in the productivity of cereals and tubers. Expansion of arable lands is modest, with increases of 1.75% for rainfed and 1.2 to 1.5%/year for irrigation. The compounded effect, as estimated in terms of NPP supply increase from the baseline to the year 2050, is around 6%.

In terms of balance between NPP demand and supply, for the food share the estimate is that the NPP demand will be around three times the supply (HANPP 272%) when also including net trade flows. Demand is only 70% of the supply for the feed share and 43% for the fuel share. Overall the HANPP is 78%.

Environmental impacts are mostly related to land degradation given a low adoption of appropriate technologies and adapted crop varieties. Integration between crop and livestock systems is the weakest, compared to scenarios II and MII. The combined effect of increased demand and limited production improvements is likely to impact very negatively per-capita consumption levels, both quantitatively and qualitatively.

Climate context: same considerations apply as for the other scenarios (see II) but with a limited capacity for adaptation measures.

Input intensification (II)

The II scenario combines:

- Favorable socioeconomic context;
- Favorable productive context;
- Unfavorable climate context.

Socioeconomic context: GDP growth in this scenario maintain high rates, at 3.5 %/year. Population growth remains at 3%/year, accompanied by increasing urbanization (FAOSTAT, 2015). Agricultural productivity improves, given the support provided to agriculture policies and the sector as a whole, with a growth rate which is mostly result of incorporating new technologies. In fact the underlying assumption for this scenario is the adoption of agricultural technologies for crop production intensification with an emphasis on "Green revolution" solutions (i.e.: high-yielding cultivars (implying improved seeds), synthetic fertilizers, irrigation, and (conventional) pest and weed control). Main relevant technologies are specified in, for instance, Blein et al. (2008), Wiggins (2014), and AGRA (2014).

Food, fuel and feed demand increase, also as a result of new consumption needs for higher-value agricultural products and given the levels of regional consumption and to ensure food security and surplus for export. New domestic markets and demands are larger than many export markets (Wiggins 2014). Market integration is fully developed, with favorable price trends for export commodities.

Productive context: production increases are the result of technological developments in the rainfed areas as well as to the expansion in irrigated areas (7 to 9%/year with corresponding high land development investments). Expansion of rainfed cultivated land in this scenario is modest, in the order of 2%/year. Based on advancements in agricultural technologies, increases in yields are assumed to be in the order of 4%/year, mainly due to productivity improvements in the case of cereals, rice, vegetables and tubers.

In terms of the balance between NPP demand and supply, for the food share the estimate is that the HANPP will be 165%. HANPP is only 71% of the supply for the feed share and 45% for the fuel share. Overall the HANPP is 75%. Despite the production improvements the increased demand is still likely to impact negatively per-capita consumption levels, both quantitatively and qualitatively.

Environmental impacts are mostly related to water consumption and irrigation and to the higher demand for fertilizer and improved seeds. Additional farming costs are associated to this. Integration of livestock (especially transhumant) systems and cropping is strengthened, especially due to management of common resources (water, rangeland), reducing conflicts in new and currently cultivated areas.

Climate context: some adaptation measures and actions are adopted, such as CSA (Climate Smart Agriculture) and IPM (Integrated Pest Management), that can counter some of the expected negative impacts of climate change; it is critical that measures are implemented early enough, as impacts are already taking place in a number of cases or are likely to be observed in the next 10-20 years (Ramirez-Villegas and Thornton 2015).

Moderate input intensification (MII)

The MII scenario combines:

- Favorable socioeconomic context;
- Favorable productive context;
- Unfavorable climate context.

Socioeconomic context: the GDP growth rate in this scenario maintains high rates, at 3.5-4 %/year. Population growth is always at 3%/year, accompanied by planned urbanization. The agricultural productivity improves, given the support to agriculture policies and to the sector at large. This is mostly the effect of incorporating new farming technologies and support to peri-urban agriculture. In fact the underlying assumption for this scenario is the adoption of CSA, IPM and EBA (Ecosystem Based Adaptation) and peri-urban agriculture technologies with a focus on moderate input intensification (AGRA 2014; Ringler, Cenacchi et al. 2014). Food, fuel and feed demand increases, given the levels of regional consumption and to ensure food security and surplus for export. In this scenario the policies and actions are designed to ensure not just economic and agriculture growth, but also an increase in food production and food security, including new urban needs for higher-value agricultural products, as well ensuring new exports products. Market integration is fully developed, with favorable trends for export commodities prices.

Productive context: production increases as the result of appropriate technological developments in rainfed and in irrigation areas. Given the assumption of a low environmental impact of agricultural technologies in this scenario, the target increases in yields are expected to be in the order of 2.5%/year (less than in II); these are especially related to local cereals and new rice varieties, as well as vegetables and tubers productivity improvements. Expansion of cultivated land in this scenario is based on a mix of new rainfed lands (2.5%/year) and new irrigation lands (3.5-5.5%/year). The support and development of non-forest and agroforestry activities is also envisaged, such as for instance the production of gum Arabic (Acacia Senegal), Shea butter (Vitellaria paradoxa), Nere (Parkia biglobosa), in particular for export. Environmental impacts are low, given the technologies and crop varieties used (e.g. improved seeds of drought tolerant cultivars, natural fertilizers, high water efficiency irrigation systems, and low environmental impact (e.g. integrated) pest and weed control. The integration between crop and livestock systems is at its best, compared to the other scenarios, both at territorial and farm level.

As to the balance HANPP for the food share the estimate is that the NPP demand will be almost twice the supply (HANPP 199% including trade flows), worse than in the II scenario. HANPP is only 72% of the supply for the feed share and 45% for the fuel share. Overall the HANPP is 78%. Despite the production improvements the increased demand is likely to still impact negatively per-capita consumption levels, both quantitatively and qualitatively.

Climate context: adaptation measures and actions such as CSA, IPM, EBA and peri-urban agriculture technologies are adopted at their best compared with the other scenarios; these can counter some of the negative impacts of climate change, but again it is critical that measures are implemented early as discussed for the BU scenario.

Extensification (EX)

The EX scenario combines:

- Unfavorable socioeconomic context;
- Unfavorable productive context;
- Unfavorable climate context.

Socioeconomic context: the GDP growth rate in this scenario is at 3%/year %/year. As for the baseline, population growth is still at 3%/year, accompanied by increasing urbanization (FAOSTAT, 2015). The agricultural production growth rate is also stable, mostly as a result of a remarkable expansion of new cultivated land (rainfed).

Food, fuel and feed demand increases in particular in urban areas and for biofuels. The overall food security status deteriorates and this requires an increase in food aid programs. Market integration, even if showing some improvements, is still unfavorable, and the agriculture sector is oriented towards commodity (e.g. biofuel) exports.

Productive context: production increases respond to growth in demand. However, these are based mostly on the expansion of cultivated lands and on a slight increase in the productivity of farming systems (Blein, Soulé et al. 2008; Wiggins 2014). Increases in yields are low, at most at 0.5%/year, and mainly related to cereals, biofuels and tubers productivity improvements. Increases in new arable land are as high as 3.8% for rainfed areas, but less than 0.75-0.9%/year for irrigation. As a result, the production of cereals, tubers and rice production covers regional demands.

As to the balance between NPP demand and supply, for the food share the estimate is that the NPP demand will be slightly less than three times the supply (HANPP 282%), worse than in the II scenario. HANPP is 79% of the supply for the feed share and 51% for the fuel share. The HANPP inclusive of all components is 88%. In all cases HANPP is the worst of all scenarios. The combined effect of increased demand and limited improvements in supply is likely to impact very negatively per-capita consumption levels, both quantitatively and qualitatively.

There are, moreover, environmental impacts which are mostly related to land clearing and land degradation, given the massive land use conversion and the low adoption of appropriate technologies and adapted crop varieties. The integration between crop and livestock systems is the weakest of all scenarios, together with scenario BU and is likely to exacerbate conflicts between pastoralists and farmers.

The **climate context** is the same as for the BU scenario.

6.3 Scenarios pathways

Pathways, drivers, transitions, alternatives

During periods of major change, important transitions and high uncertainty, using "single lens" through which to explore the changes of tomorrow is probably limited (Shell 2013). In this light there is a need to take a broader perspective to investigate, with reference to the scenarios defined in this study, different possible pathways or trajectories.

Scenarios pathways offer this perspective, enabling us to explore different possible futures and to bring into sharper focus the possible outcomes of needed choices and available alternatives (Shell 2013; Africa Progress Panel 2014).

It is likely that, in the near future, the Sahelian region will contain a mix of elements and characteristics found in every scenario (Lambin, D'haen et al. 2014).

Also given the socioeconomic and environmental vulnerability of the Sahel region this seems, therefore, an appropriate logical framework which allows evaluating and designing alternatives pathways and transitions. By investigating impacts, synergies (co-benefits), trade-offs and crosslinked effects the aim is to assess the possible limitations, constraints and collapses for sustainability of the region. Given the great uncertainties for instance in relations to the possible impacts of climate change on agricultural productivity and in the fluctuations in commodity prices, make this an exercise of "visualization" and not an estimate of the effects and changes in consumption patterns, food supply and demand in the Sahel region.

In this section we will explore such pathways as a narrative, but always with reference to the outcome of the modelling. This is in function of the climatic, socioeconomic and productive contexts and with reference to:

- main changes driving the scenarios;
- the most important transitions within and between scenarios;
- possible scenarios tipping points and trapped transitions than can lead to collapses;
- possible scenario alternatives.

The next section discusses the general overview of this analysis of the scenarios, in function of the contexts, pathways, alternatives, possible transitions, "tipping points" and "trapped transitions".

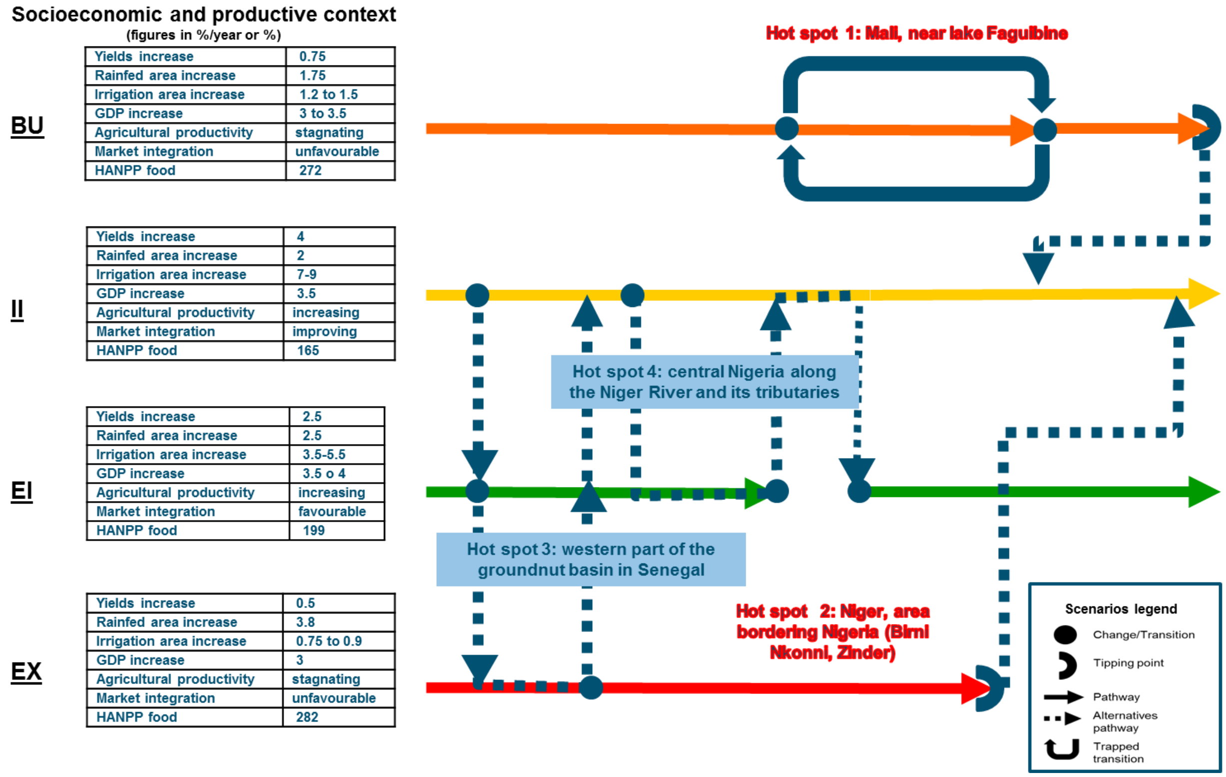


Figure 10: Contexts, pathways and transitions for the scenarios

Source: Own estimates and elaboration

Illustration of some scenario pathways

As a starting point it is important to note that, as a result of the modelling, the picture for HANPP is rather worrying. For the food share alone, HANPP ranges from 115% in the baseline, to 165% and 199% respectively for the II and MII scenarios, and to 272% and 282% for the BU and EX scenarios (in all cases adding net trade flows at the year 2012 levels to the NPP supply). The implication for the pathways and trajectories, for all scenarios, is that the food share is not sufficient to compensate for a growing demand which is in fact expected to more than double by the year 2050. In the case of feed HANPP is ranging from 68% to 78% in function of the scenarios, in any case below 100%. The same applies to the fuel HANPP, which ranges from 43% to 51% depending on the scenarios.

In the BU scenario (In Figure 10 the BU main pathway is represented in orange and alternative pathways in dashed black), after an initial expansion phase of cropland area and due to an important increase in pressure on natural ecosystems, a second phase starts which goes towards jeopardizing the already fragile equilibrium between pastoralists and farmers (Lambin, D'haen et al. 2014). The level of integration and management achieved between crop and livestock system is limited, with rising conflicts especially between nomadic and transhumant systems and sedentary agriculture. In response to a general drying up of land due to climate change, rural households tend to sell their animals or migrate temporarily or permanently to wetter areas or elsewhere.

The Sahel enters in a "trapped transition" (in bold black) fed by continuous cycles of food insecurity, poverty, overgrazing, land degradation, decreases in yields, water scarcity, conflicts and famines. Rural communities invest less in agricultural intensification and are much more vulnerable to the consequences of climate variability and climate change (i.e. droughts, floods). At the end of this trapped transition, a tipping point is reached (e.g. the HANPP for the food share reach 300%), where the only alternative would be to move towards a new pathway of agriculture intensification. The context of this new pathway, however, implies lager capital and human investments, given the high vulnerability of rural communities, and the increase in poverty and the cumulated environmental degradation with the associated economic costs to restore degraded lands. This all lead to the need for important improvements in infrastructures to increase access to markets and expand irrigation and intensive agriculture altogether.

In the II scenario (the II pathway is in yellow and alternative pathways in dashed black), policies and strategies are in place to support a transition towards intensified land use and agriculture (Africa Progress Panel 2014). Large investments are made in the early stages in infrastructures for agriculture intensification and accessibility to link urban and rural areas within countries as well as between countries (Laurance, Sloan et al. 2015). The objectives of regional and national self-sufficiency in food supply and the support to the agricultural processing industry are heavily sustained by the national states (Lambin, D'haen et al. 2014). International capital investments go into the development of large monoculture farms and agricultural regions specialize in specific commodities. These land developments also entail the cultivation of large tracts of savannah and grasslands as well as croplands, often at the expenses of smallholders (Cotula 2009; Lambin, D'haen et al. 2014). The land use includes biofuel and fibre production. It often entails intensive farming practices (e.g. mechanization, chemical fertilization, inappropriate water management techniques) possibly leading to soil degradation and exhaustion.

Agricultural production is generally focused on cash crops for a global market, with large investments in irrigation and application of pesticides and fertilizers (Ringler, Cenacchi et al. 2014). The level of integration between livestock rising and crop production improves, but conflicts between pastoralist systems and farmers persist, especially in the new land developments. Even with such high technological input investments, the food share alone is far from reaching the demand with an HANPP of 180%. This drives to the need for further land expansion in particular of irrigated and intensive rainfed agriculture, as well as for restoration and rehabilitation of degraded lands. As a result, there are increasing requirements in terms of water consumption, input uses and investments. Even with increasing market integration, the regional agriculture sector is dependent on fluctuating markets and international prices. As a result, after some years of successful agricultural intensification, food insecurity and poverty in the region increase and the agriculture system becomes more vulnerable to external prices and trade changes. Environmental concerns may drive towards diversified agricultural systems leading to "greener" pathways to address social impacts and degradation of natural resources (e.g. salinization and soil pollution and degradation; contraction of smallholders agricultural land; limited level of livelihood diversification). However, as it will be discussed in the next section, this pathway does not represent an improvement in the food security status.

In the MII scenario (the main MII pathway is in green and alternative pathways in dashed black), policies and actions are oriented to ensure the integrity, resilience, restoration and sustainable management of landscapes, based on integrated land management at the regional, national and local scale. This includes, among others, the adoption of CSA (Climate Smart Agriculture) actions, IPM (Integrated Pest Management), EBA (Ecosystem Based

Adaptation) and peri-urban agriculture technologies with a focus on moderate input intensification (Ringler, Cenacchi et al. 2014; Munang, Mgendi et al. 2015), as well as a broad support to research and development in the cited domains. Agroforestry and farming practices combining crop and livestock systems are widely adopted, increasing soil fertility. Improved management of water and rangeland resources at territorial level reduces conflicts between transhumant livestock systems and agriculture. There is a strong focus on the multi-functionality of agriculture and on landscapes proactive approach to ecosystem management including techniques of soil conservation, water harvesting, soil fertilization and ecological restoration which are generally integrated in farming systems (Blein, Soulé et al. 2008; Lambin, D'haen et al. 2014). Tree plantations, non-forest production systems, green belts and water conservation projects are flourishing. Developing and using for instance CSA intensive agriculture management techniques, it will be possible to promote integrated land management for multifunctional agriculture uses, and new outreach and extension agriculture services to ensure the development and use of new varieties of locally adapted crops. Some of the future transitions in this scenario are towards a higher degree of societal resilience to climatic variability and climate change implying a less climate-dependent economy (Africa Progress Panel 2014; Lambin, D'haen et al. 2014).

Nevertheless due to the lower productivity of the cropping systems in this scenario, the need to provide food, feed, fuel and fibre in a sustainable way results in a worsening food security status. This makes it nearly impossible to solve the equation "food supply/demand" to ensure regional food security. The expected consequence is a further expansion of rainfed areas and possible transitions to the II or even EX scenarios.

In the EX scenario (The EX pathway is in red and alternative ones in dashed black), we expect that increases in agricultural production are achieved solely through the expansion of rainfed land. This is to be ascribed to small holder agriculture as well as to important increases in large monoculture farming at the expenses of savannah areas, in the latter case with possible reduction of the land available of to the smallholders (Cotula 2009; Lambin, D'haen et al. 2014). Large tracts of natural areas are converted into croplands to be cultivated extensively, for instance for cash crops, biofuel or fibre, with the consequent degradation and exhaustion of soils. The level of integration between livestock and crop farming is at the minimum, with increasing conflicts between pastoralists and farmers exacerbated by the expansion of cropping areas. Most of the socio-economic and environmental effects already described in the BU scenario apply here as well, although these are worsened.

As a result, the food insecurity and poverty status in the region worsens (e.g. the HANPP for food is around 330%, meaning that demand is three times the NPP supply), and the agricultural system is made more vulnerable to external prices and trade changes. After some years of apparent success due to the cultivation of new land, the scenario goes towards a tipping point with consequences in terms of food security, poverty, overgrazing, land degradation, decrease in yields, water scarcity, conflicts and famines, "pushing" towards alternatives pathways. The long term implications are costly reconversions towards more intensive and diversified agricultural systems, including the restoration of degraded lands and all costs related to ever-increasing out migrations.

To better illustrate the analysis of pathways and link it concretely to specific cases and areas a more detailed analysis of the '"hot spots" (or constraints) and "hope spots" (or opportunities) resulting from the scenario modelling was carried out and is given in the next section. This was done with reference to the baseline situation as well as to all future scenarios elaborated in this study. In all cases the locations were scrutinized in terms of pathways, important transitions, underlying drivers, and specifying where tipping points and trapped transitions are reached.

In Depth Analysis of Selected “Hot spots” and “Hope spots”

The results of the scenario modelling can help to identify, by comparing the NPP supply and demand in their different components, areas of concern and areas of opportunities. These can be named respectively as “hot spots” and “hope spots” (Ericksen, Thornton et al. 2011; UNEP 2013). For instance, it is possible to identify “hot spots” in relation to rainfed agriculture with consequences for agriculture productivity and food availability and food security at large. But it is also is possible to identify “hope spots” for successful water management and rainfed and irrigated agriculture with positive consequences for agricultural productivity and rural communities.

From the maps of “hot spots” and “hope spots” generated from the scenario modelling, a few examples are selected for an in-depth analysis. This is especially useful to get better insights (and in a way “validate”) the exercise conducted for the whole of the Sahel. It also helps in understanding specific drivers intervening at the sub-national and local level, as well as in gathering good practices, lesson learned, and possible ways of scaling them up. Examples refer to the BU scenario but were selected whenever occurring in all scenarios for both the food and feed components.

The four examples of “hot spots” and “hope spots” are located in Figure 11.

“Hot spots”

Example 1: Mali, near lake Faguibine

This example of a “hot spot” shows a good case of trapped transition (Ericksen, Thornton et al. 2011; UNEP 2013; UNEP n/d). This type of transition occurs when entering in a cycle of degradation-poverty-overexploitation-food insecurity which is very difficult to break (see Figure 10). Given the present climate variability, droughts affect water availability, with a decline of water volumes and even the complete drying up of lakes and reservoirs (like in the case of Lake Faguibine). This is exacerbated in perspective of climate change and population increase. The sparse rainfall is not enough to support rainfed agriculture and cannot fill the lakes and reservoirs without inflow from distant parts of the Niger Basin where the rainfall is higher. Apart from the negative effect on the expected irrigated agriculture, other sources on which local livelihood systems are based are also affected including rainfed agriculture, fishing, and dry-season livestock grazing. This is analyzed under the conditions of the BU scenarios but even is this may improve with the access to some low inputs technologies, the consequences are the about same. Climate variability and change, cumulated with environmental degradation and increase in food and feed demand, result in a dramatic increase in the pressure of livestock and farming around lakes and reservoirs, with resulting decrease in food, feed and fuel supply. Given these current and expected environmental and socioeconomic conditions all possible farming options (e.g. traditional with low inputs, intensive with high input, or climate smart with water/soil management) and other livelihood practices such as fishing, fuelwood and pastoralism, are difficult or impossible to sustain without an extensive and long term program of rehabilitation and restauration and without important land uses changes (Ericksen, Thornton et al. 2011; UNEP 2013; UNEP n/d).

Example 2: Niger, area bordering Nigeria (Birni Nkonni, Zinder)

The second example of "hot spot" was selected in Niger in the areas at the border with Nigeria (Birni Nkonni, Zinder, etc.). The example shows a typical case of possible tipping point transition. In this case the cumulative effects of climate variability, land use changes, agricultural activities and food demand increase, all lead to an alarming level of HANPP under the BU scenario. Areas under rainfed agriculture grew already in the past with the loss of a large portion of the natural vegetation (e.g. Baban Rafi Forest in Niger) (UNEP 2013; UNEP n/d) and this trend may well continue with the remaining woodlands been degraded by overexploitation for fuelwood and non-wood forest products. The intensity of demand for agricultural land has also led to a near continuous use of farmland in the area, with shortened or no fallow period for it to recover fertility. Continuing population growth will put further demands on this already dramatically changed landscape. Even in the case of intensification or ecological management (e.g. water/soil management practices, climate smart agriculture) the situation will continue worsening, in particular in a context of climate change, and given the high increase in food demand. However there are areas neighboring this hotspot (e.g. Maradi in Niger or further south, in Nigeria) where conditions are favorable and indicate a different pathway. These are especially areas with good potential for agroforestry practices, based on wooded dominated species, which can contribute to restore/rehabilitate the degraded landscapes and in this way increase the resilience of small farmers to improve their livelihood (Ericksen, Thornton et al. 2011; UNEP 2013; UNEP n/d).

"Hope spots"

Example 3: western part of the groundnut basin in Senegal

This "hope spot" is a good illustration of an alternative pathway. Obviously alternative pathways imply different impacts and effects on agriculture productivity, population livelihood in urban and rural areas, and food supply. The Groundnut Basin, Senegal's major agricultural region, as many other areas of West Africa, has experienced, over the past, loss of woodland and forest cover due to the expanding cultivations (UNEP 2013; UNEP n/d). In our example we are referring especially to the western and northern part of the basin. High and rising population densities with the consequent extension of cultivated lands over often fragile natural environments lead to a declining soil fertility and eventually to severe degradation in fragile and endangered natural environments, as well as to the detriment of pasture and forested areas. Stagnation of production is one of the obvious consequences linked to the lack of valorization and diversification of rural production and activities. This further hastens out-migration from rural areas to cities and abroad. As a result of these more recent processes, this area is witnessing the opposite situation now: abandoned agricultural lands are turning into tree-dotted savannas, where groundnut and millet farming systems prevailed in the past, allowing now some restoration of soil fertility. However this phenomenon is not the result of a planned land management program. Rather, it stems from recent trends in out-migration to cities, with high negative impacts on urban poverty and food demand/supply balance at country level. The drop in world market prices for groundnuts, the variability in rainfall regimes, and the removal of government agricultural subsidies have all made it difficult for farmers in the region to continue to earn a living. Those who have stayed in the area are enjoying the benefits of a revived rotational fallow system, large tracts of grazing land for a growing livestock economy, and diversification into other cash crops.

Example 4: central Nigeria along the Niger River and its tributaries

This “hope spot” is an example of a possible transition based on appropriate agriculture technologies (in particular intensification and ecological management). These areas of Nigeria receive sufficient rains (up to 750 mm) to sustain and increase production for rainfed agriculture and pastoralism (Ericksen, Thornton et al. 2011; UNEP 2013; UNEP n/d). The presence of the Niger River and its tributaries provides an important opportunity for irrigation.

However, climate variability implies the use of adequate agriculture technologies (such as those underlying II and MII scenarios) and requires better training and farm advice to farmers as well as major investments in infrastructures, irrigation above all, as well as food processing and transport. In areas with irrigation potential (e.g. Challawa Dam in Kano State, Nigeria), dams could help to control flooding caused by seasonal and variable rainfall, to support irrigation and provide water to populated places. Nevertheless special attention needs to be given to swamps and wetlands controlled by seasonal rainfall. Reductions in the annual flooding extent has put the wetlands at risk and reduced the economic and environmental benefits they provide, including agriculture, cattle, fuelwood, fish, shallow aquifer recharge, and habitat for migratory and local bird species (UNEP 2013; UNEP n/d). Growing conflicts between livestock rising and agriculture, especially in view of expanded irrigated schemes, can also be expected, and common resources such as water and pasturelands should be managed carefully. Recently, a combination of various programs (government lead and also supported by private investors) and projects as well as farmer initiatives have led to significant revitalization in many of the mentioned areas. Success stories are also reported in the domain of agro-forestry. This transformation of the land has reduced drought vulnerability and will help people diversify their livelihoods which will then rely not only solely on rain-fed crops.

7 Limitations of this Study

Although there are varying definitions of “scenarios” there is consensus on one point: scenarios are not about prediction (Van der Heijden, Bradfield et al. 2002). Scenarios can be regarded as consistent and coherent descriptions of alternative hypothetical futures reflecting different perspectives on past, present, and future developments, and which can serve as a basis for action.

Apart from the general limitations inherent in all scenario approaches, there a number of specific shortcomings with reference to the data and the approaches used in this study.

The limitations in some of the statistical data used have been already discussed. This refers namely to the risk of over-reporting in domestic food production statistics (due to shortcomings in the official statistics of the countries concerned) as well to the underreporting in the food trade statistics (due to informal flows and again in possible shortcomings in the statistical systems). Moreover with regards to food trade statistics, the 2012 figures are used in the scenarios. Altogether these biases may limit the reliability of the approach, originally developed by Abdi et al. (2014) and also followed in this study (although integrated with net trade flows, which uses domestic food production as the best available proxy for food demand).

The study did not include projections of future shifts in diet in the region, providing a very conservative view of the potential imbalances between NPP supply and demand. Demand in the estimation is only modeled as expanding following population growth, but changes in the nature of the demand were not included in the model.

There is also the possibility that NPP is underestimated by MODIS in case of very low cropping densities, which do occur of course in the Sahelian farming systems. This aspect should be further investigated and analyzed in its impact on the overall NPP supply estimates.

Also, although the best available sources were used for “mapping” the land utilization types (LUTs), there are known limitations in the accuracy of the input data (i.e. the MapSPAM database from IFPRI). Further limitations relate to the accuracy of other datasets used as inputs in the study, such as the land cover for the not crop LUTs.

The assumptions underlying the different scenario encompass simplified relations between input and output (yield) levels: these “coarse” assumptions were also made purposely, to achieve sufficient “contrast” between the same scenarios.

The effect of climate change has been modelled using relevant studies on the impact of yield reductions for SSA and the Sahel. However these references are too generalized and often even contradictory. A spatially explicit and crop specific modelling approach under the new RCPs and SSP scenarios would represent a useful advancement.

Apart from the input data there are limitations in the scenario modelling which was developed based on a GIS approach. This approach allows the implementation of simple rules which may overlook more complex determinants for instance in the transition towards different LUTs under specific scenario assumptions.

Moreover the effect of CC accounted for was limited to crop yields (the food share) and did not include rangeland or woodland covers with the respective feed and food shares.

8 Concluding Remarks

The overall human appropriation expressed in terms of net primary production (HANPP) projected for the year 2050 as estimated in this study, ranges between 75% and 88%, depending on the agricultural scenarios. This indicates a significant change and deterioration of the resource-use balance for Sahelian countries when compared to the year 2010 baseline situation, where the HANPP was estimated at 29%.

Looking back at existing studies, even with differing time spatial scopes and often adopting different methodological approaches, show similar trends. For instance Abdi et al. (2014) in a study targeting 22 countries in sub-Saharan Africa concluded that around 41% of the NPP supply is currently consumed by humans, without considering food trade flows. Based on the same spatial extent and approach to HANPP, Ardö (2015) projects NPP demand and supply to the year 2030. Its estimates point to an increasing vulnerability of the area, with HANPP ranging from 67% in the Sahel to 200% or more in the northern countries. Paillard et al. (2014) also expect SSA having a higher food consumption per person in 2050, to experience a deficit in the calories requirement from plant and animal biomass. This unbalance, ranging from 5 to 50% of the caloric needs, depending on the scenario and diets, can be responded to by imports from other surplus regions of the world. Fetzel et al. (2016) with reference to the whole of West Africa indicate an increasing trend (+ 84%) of HANPP from 1980 to 2005. They also highlight decreases in per capita HANPP in 3 Sahelian countries over the same period: Senegal, Chad, Nigeria. Blein et al. (2008) in their study covering the whole of West Africa indicated that especially the humid and semi-humid areas have the production capacities and the necessary resources to achieve food security over the next 25 years. The Sahelian and Sudano-Sahelian zones, however lag behind due to progressive aridification and steady population growth. Finally, van Ittersum et al. (2016) also point to the importance of the current SSA 20% imports of its five main cereal needs. Closing the existing yield gap alone on existing cropland area (from 20% to 50% or even to an optimistic 80%) is not expected to be enough to respond to future population growth to the year 2050.

When focusing on the food share of our estimates, the baseline already suggests a delicate resource-use balance about biomass for food with 115% of the NPP supply, including both domestic production and recorded imported food (as 100% of NPP supply is expected, the additional 15% percent is due to measurement imperfections in domestic production, import records and biomass equivalences). By the year 2050, food demand ranges from 165% of the NPP supply in the performing scenario ("Input Intensification") to 282% in the worst performing one ("Expansion") missing the indicator for self-sufficiency.

The remaining two scenarios ("Moderate input intensification", with an HANPP for food of 199% and "Business As Usual", with an HANPP of 272%) give intermediate results. These figures also take into account the net trade flows of food as of today's magnitude. Optimal agricultural productivity is necessary but not sufficient to keep the pace of a more than doubling population growth in the Sahel region, as calculated using the latest UN DESA projections (2015).

One may conclude that, for most if not all of the Sahelian countries analyzed, food security may only be achieved broadening intervention beyond agriculture policy and investments to embrace complementary policy sectors. The current importance of trade in providing food imports (estimated at 13% of the food biomass equivalent of total current consumption) is expected to play a significant and increasingly important role in responding to future food needs. The expected changes in food consumption patterns by 2050 (although not accounted for in modelling food needs of 2050 in this analysis) are foreseen to raise the importance of imports and hence trade policy as a tool in the food security policy kit. In the region, this may translate into the harmonization of standards, a more systematic adherence to regional agreements and the evaluation of the long term impact of the frequent trade bans on FNS. Infrastructure policy has also a role to play to reduce transport costs. At the same time, the projected evolution of HANPP also points to the increasing need of diversification of the economies of the region. Hence, FNS is also likely to depend on successful diversification policies.

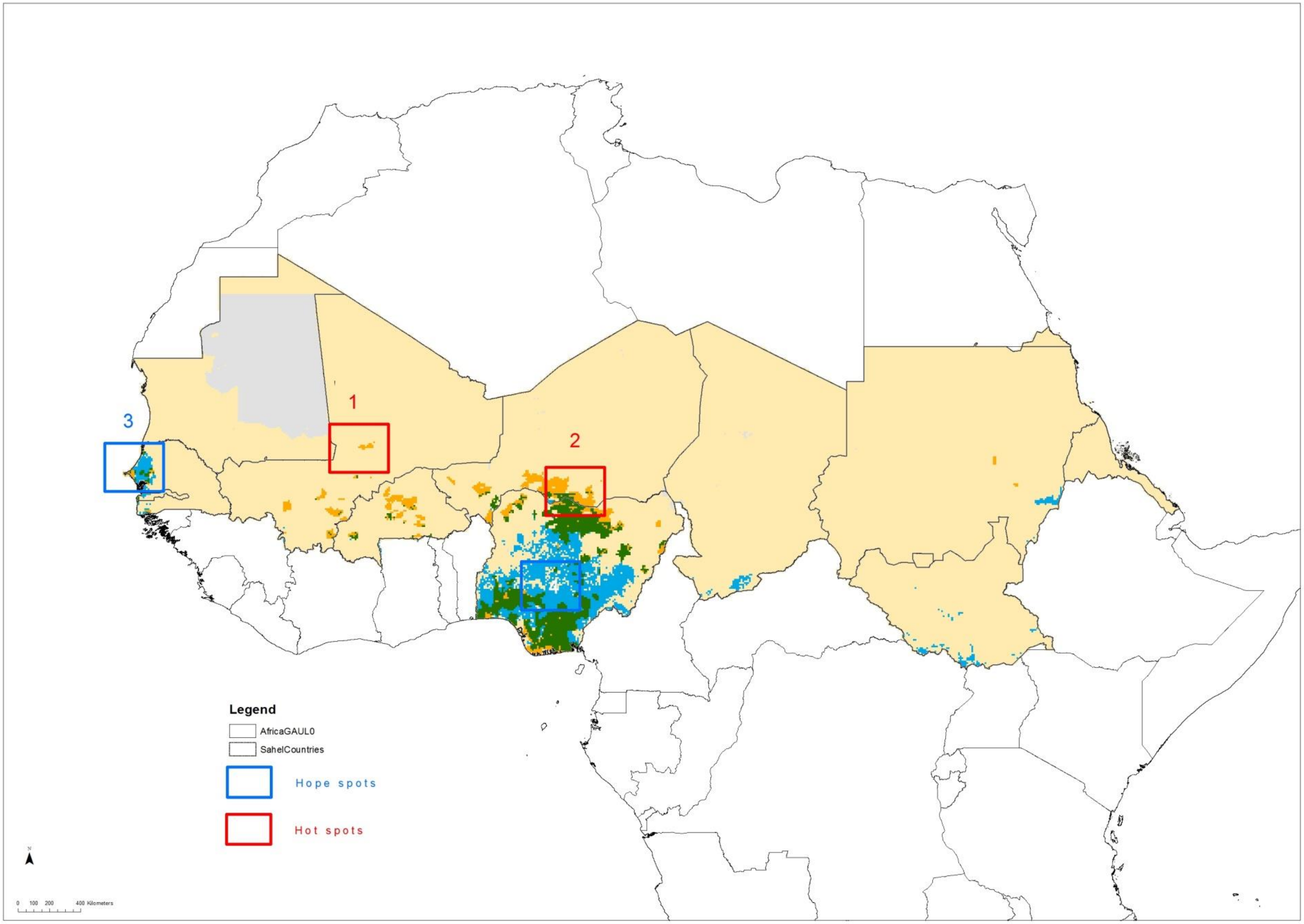


Figure 11: Selected "hot spots" and "hope spots" for the in-depth analysis, BU scenario. (Source: Own elaboration)

Appendices

Appendix I: Review of the literature commented references.

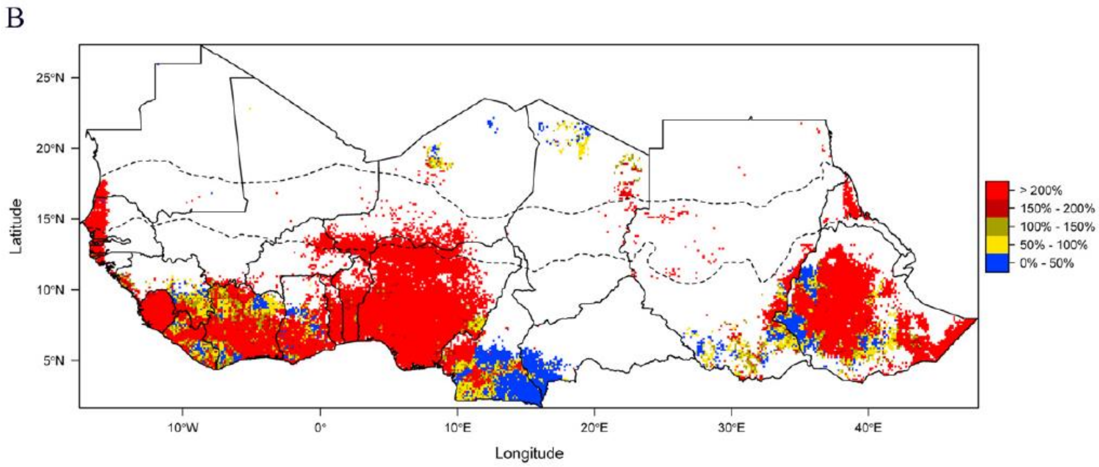
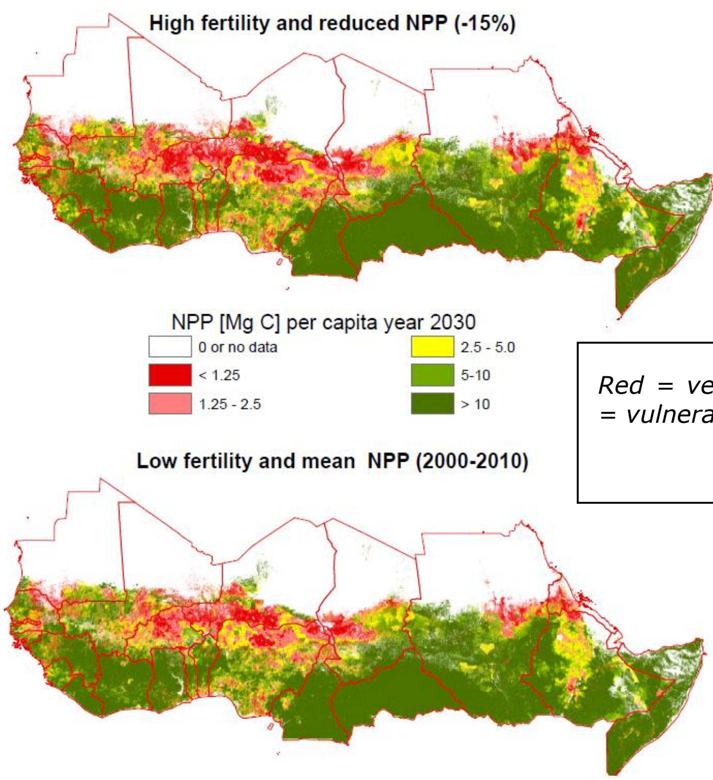


Figure 12 NPP Demand relative to NPP Supply between 2000 and 2010
Source: Abdi et al. (2014)



Red = very vulnerable, pink = vulnerable

Figure 13 NPP per capita for the year 2030 in the Sahel region
Source: Ardö (2015)

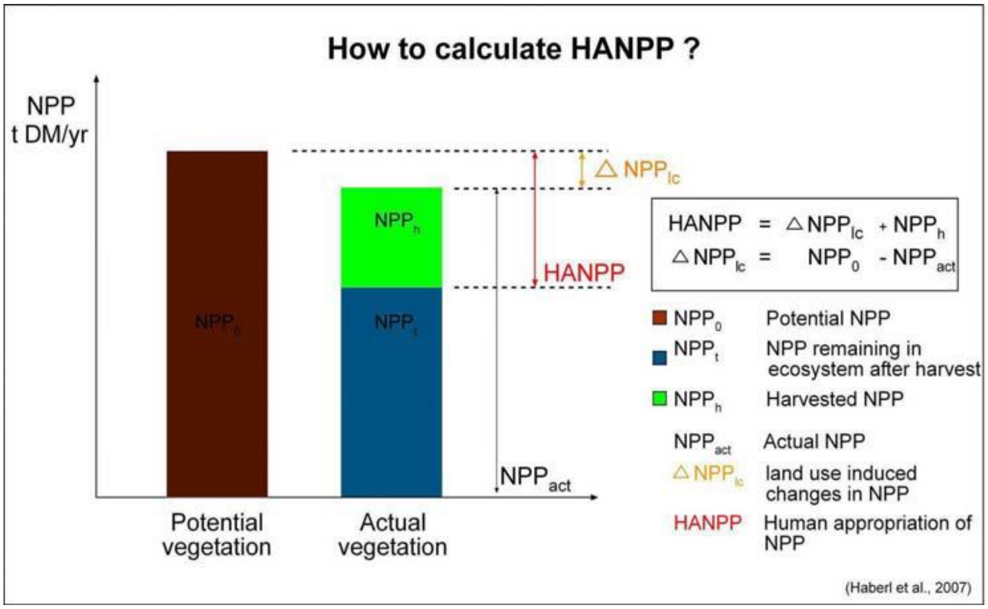


Figure 14 Calculation of HANPP
Source: Fetzel et al. (2012)

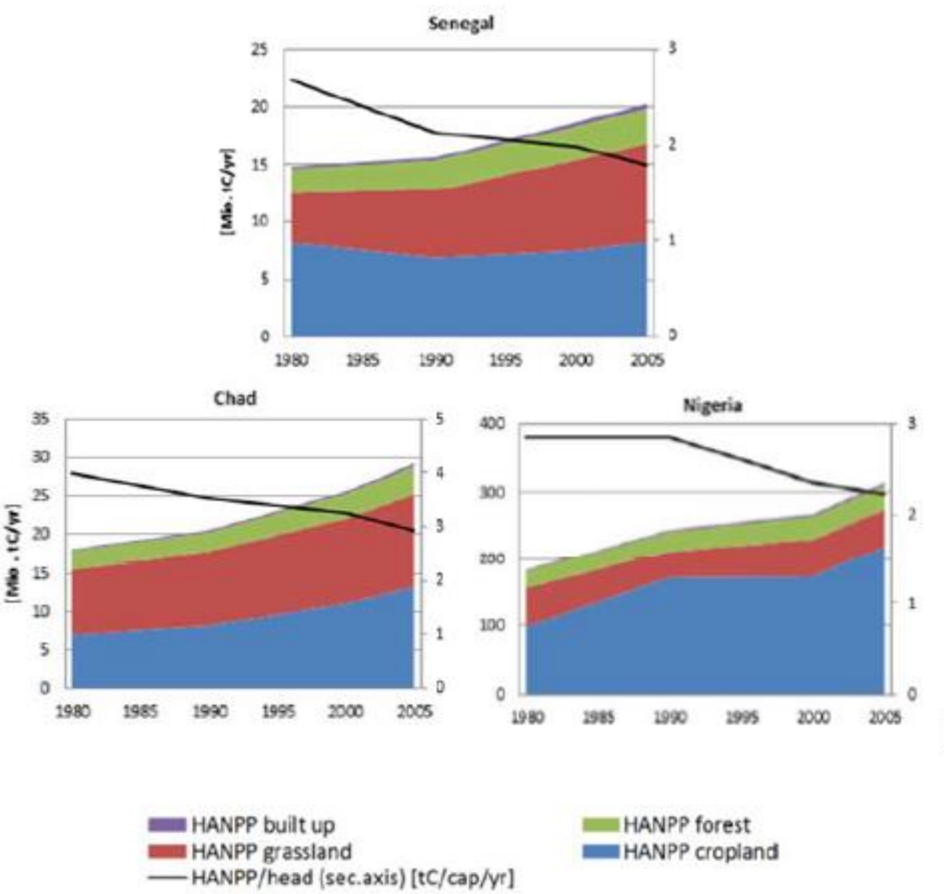


Figure 15 HANPP trends in Mio t C per year for selected countries.
Source: Fetzel et al. (2012)

Country	2010 Yield (MT/ha)	2010 Area (thousands of ha)	2010 Production (MT)	2050 Yield (MT/ha) Min	2050 Yield (MT/ha) Max	2050 Area (thousands of ha) Min	2050 Area (thousands of ha) Max	2050 Production (MT) Min	2050 Production (MT) Max
Benin	0.90	211	190	1.96	2.06	375	385	739	787
Burkina Faso	1.02	1,594	1,632	1.86	2.08	1,952	1,981	3,638	4,109
Côte d'Ivoire	0.62	107	67	1.25	1.29	167	171	210	219
Gambia	1.64	25	41	3.51	3.59	41	42	144	151
Ghana	0.95	369	352	2.04	2.09	631	647	1,290	1,342
Guinea	0.63	10	6	1.40	1.43	8	8	11	12
Guinea-Bissau	0.99	27	27	1.97	2.05	45	46	89	93
Mali	0.86	983	846	2.70	3.03	1,142	1,176	3,142	3,517
Niger	0.46	2,329	1,075	1.19	1.42	2,724	3,360	3,847	4,241
Nigeria	1.15	8,412	9,675	2.04	2.13	9,947	10,145	20,336	21,617
Senegal	0.79	188	149	1.74	1.77	315	323	550	571
Sierra Leone	1.91	10	20	2.83	2.88	14	14	39	41
Togo	1.16	236	274	2.32	2.45	321	329	747	803

Source: Based on analysis conducted for Nelson et al. (2010).

Figure 16 Sorghum production changes in West Africa
Source: Jalloh et al. (2013)

Product group	Surface area	Production	Yields	Surface area	Production	Yields	Surface area	Production	Yields
	Forecast for 2020			Forecast for 2030			Evolution 2030/2005		
	ha	t	kg/ha	ha	t	kg/ha	%	%	%
Products for regional consumption									
Dry cereals	40 642 699	57 499 073	1 415	45 072 761	76 158 180	1 690	130	202	156
Rice	7 250 861	11 365 003	2 267	9 150 796	14 036 858	2 480	179	170	153
Roots and tubers	23 786 888	264 627 723	11 125	39 972 879	473 728 910	11 851	366	429	117
Vegetables	3 359 623	24 728 584	7 361	4 340 185	35 817 389	8 253	190	252	133
Fruit	4 507 185	28 942 356	6 421	5 749 183	39 687 478	6 903	184	220	120
Legumes	15 517 175	8 723 500	562	21 549 909	13 795 751	640	219	315	144
Sugar cane	142 907	4 112 850	28 780	163 486	4 001 906	24 479	140	93	67
Tobacco	72 116	50 030	850	82 072	64 990	1 068	138	192	188
Sub-total	95 279 454	400 049 119	4 199	126 081 271	657 292 062	5 213	190	333	175
Products for export outside West Africa									
Coffee, cacao & tea	7 549 911	4 061 680	677	9 157 937	5 056 226	809	162	173	156
Cotton	4 594 199	4 920 523	1 071	6 831 191	7 703 903	1 128	270	307	114
Rubber	898 426	607 793	677	1 229 498	789 866	642	219	193	88
Palm	6 233 563	21 029 053	3 374	8 051 843	27 248 384	3 384	190	191	101
Groundnuts	7 772 464	12 296 518	1 464	10 601 769	20 066 654	1 664	217	340	138
Pineapples & bananas	290 895	2 965 350	10 194	347 101	3 758 559	10 828	156	181	116
Walnuts	3 015 796	3 590 680	1 191	5 627 297	8 146 505	1 448	476	775	163
Sub-total	30 355 254	49 471 597	1 630	41 846 636	72 770 097	1 739	217	250	115
Total	**125 634 708**	**449 520 716**	**3 578**	**167 927 907**	**730 062 159**	**4 347**	**196**	**322**	**164**

Figure 17 Summary of results obtained for the various scenarios
Source: Blein et al. (2008)

The maximum sustainable exploitation level of the production limiting resource, the maximum sustainable production of desirable products, and the maximum sustainable population densities, in four climatic zones in the Sahel region, for a relatively dry year; actual population densities (1990), and the ratio of resource-based to actual population densities (based mainly on Breman, 1992)

	North Sahel	South Sahel	North Sudan	South Sudan
Annual rainfall (mm)				
Average	250	475	750	1050
Dry year	150	300	575	875
Production limiting factor	Water	Nitrogen	Nitrogen	Nitrogen
Maximum sustainable exploitation level of limiting factor	150 mm	0.5 t km^{-2}	1.2 t km^{-2}	1.9 t km^{-2}
Maximum sustainable production of products				
Livestock (TLU[5] km^{-2})	3[1]	20[2]	20[2]	10[3]
Grain production (t km^{-2})	2.5	2.5	8.5	12.0
Population density based on integrated land-use[4] (km^{-2})	1	11	36	51
Actual population km^{-2} (1990)	1	13	33	37
Ratio resource-based/actual population density	1.0	0.8	1.0	1.4

[1]Nomadic livestock system.
[2]Transhumance livestock system.
[3]Sedentary livestock system.
[4]Integrated land-use does not imply adding livestock and grain production levels.
[5]TLU, tropical livestock unit (a hypothetical animal of 250 kg).

Figure 18 Maximum sustainable production levels & population density
Source:Kessler (1994**)**

Review of state of the art of methodologies for estimating NPP and carrying capacity in developing contexts

Basic studies on the concept, methods and different uses of carrying capacity, NPP and HANPP

KEY REFERENCES:

Imhoff M., L. Bounoua, P. Zhang and R. Nemani. 2010. "Satellite Supported Estimates of Human Rate of NPP Carbon Use on Land: Challenges Ahead". NASA Goddard Space Flight Center and Ames Research Center, Fall AGU Meeting, San Francisco, CA, USA. http://www.nasa.gov/pdf/505659main_NPP_pressbriefing_slides_MLI.pdf

Good application and review of the state of the art of the HANPP methodologies but without an assessment for the African region and of possible trends and implications. The study presents trends and implications at regional level for food security and for land management.

Krausmann F., K.H. Erb, S. Gingrich, H.Haberl, A. Bondeau, V.Gaube, C. Lauk, C. Plutzar, and T. D. Searchinger. 2013."Global Human Appropriation of Net Primary Production Doubled in the 20th Century." Proceedings of the National Academy of Sciences 110, no. 25 (June 18, 2013): 10324-29. http://www.pnas.org/content/110/25/10324.full.pdf

Excellent review of the state of the art about HANPP methods and use of data with a global perspective and with actual trends.

Lane M., 2010, The carrying capacity imperative: Assessing regional carrying capacity methodologies for sustainable land-use planning, Land Use Policy 27: 1038–1045.

http://www.sciencedirect.com/science/article/pii/S0264837710000074

Exploration of main carrying capacity methodologies and limitations. Good comparison of different methodological approaches and data needed. Guidelines for implementation.

UNEP, 2012, One Planet, How Many People? A Review of Earth"s Carrying Capacity, A discussion paper for the year of RIO+20, UNEP Global Environmental Alert Service (GEAS).

https://na.unep.net/geas/archive/pdfs/GEAS_Jun_12_Carrying_Capacity.pdf

Global view of main drivers and trends in carrying capacity, useful as a reference in scenario development.

UNEP, 2013, From "hot spots" to Hope spots: Connecting local changes to global audiences, UNEP GEAS Series.
http://na.unep.net/geas/getUNEPPageWithArticleIDScript.php?article_id=102

Good attempt to use satellite imagery and carrying capacity outputs to assess potentialities and limitations of ecosystems in order to provide evidence of dynamic of changes.

Zica M., Erb K, 2009, The global loss of net primary production resulting from human-induced soil degradation in drylands, Ecological Economics 69 (2009) 310–318.

Global estimates of NPP losses caused by human-induced dryland degradation, including SSA and Sahel. The findings can be used to assess trends in land use change and identify strategies aimed at reducing dryland degradation as an option to sustain future population numbers without putting further pressures on dryland ecosystems.

Applied studies of NPP, HANPP and carrying capacity for SSA and Sahel

KEY REFERENCES:

Abdi A., J. Seaquist, D E Tenenbaum, L Eklundh, J. Ardö, 2014, The supply and demand of net primary production in the Sahel, Environ. Res. Lett. 9 (1:11).
http://iopscience.iop.org/article/10.1088/1748-9326/9/9/094003/pdf

A good attempt to adapt the concept of NPP (supply and demand) at regional scale. Good use of available data to assess the actual state and trends in NPP to evaluate regional vulnerability. Methodology can be used to assess past trends related to land uses and population changes. Good assessment of uncertainties and limitations of the methods with FAO data and other data sources. Nevertheless, lack of assessments and insight about future or plausible evolution of trends and changes related to main drivers such as population change, land use and land cover changes and near future climate variability and future climate change.

Paillard, S., S. Treyer, et al. (2014). Agrimonde–Scenarios and Challenges for Feeding the World in 2050. Versailles, Editions Quæ, Springer Science & Business Media.

This reference relates to the large project of CIRAD and INRA analyzing world's food and agricultural systems on the 2050 timeline. It is based on statistical references for the period 1961 to 2003, and uses the Agribiom simulation tool to calculate food biomass resource/use balances. Two normative scenarios on the 2050 timeline are considered.

A limitation of Agrimonde consist in the spatial aggregation of the outcomes.

Ardö J., 2015, Future per capita availability of net primary production in rural Sahel - potential effects of the interplay between population growth and climate change, Physical Geography and Ecosystem Science Lund University, Lund. http://www.appg-popdevrh.org.uk/Future%20per%20capita%20availability%20of%20net%20primary%20production%20in%20rural%20Sahel.pdf

This paper tries to assess the potential effects of climate change on the future availability and provision of food in the Sahel, based on local supply and demand of resources. Assesses actual and derives possible future (2030) NPP trends with low/high fertility population scenarios. Nevertheless NPP and HANPP are not only related to population and the work lacks exploring other drivers (e.g. land use change, market orientation, yield gaps, climate variability and change). It applies the same methodology as in Abdi et al., 2014.

Fetzel T., M. Niedertscheider, K. Erb, V. Gaube, S. Gingrich, H. Haberl, F. Krausmann, C. Lauk, and C. Plutzar. 2012. "Human Appropriation of Net Primary Production in Africa Patterns, Trajectories." Institute of Social Ecology IFF - Report commissioned by: United Nations Conference on Trade and Development Division for Africa, Least Developed Countries and Special Programmes. Social Ecology Working Paper Number 137. Faculty for Interdisciplinary Studies (Klagenfurt, Graz, Vienna).

https://www.uni-klu.ac.at/socec/downloads/WP137_webversion.pdf

The most complete work on HANPP methodologies and their application to Africa, including changes in productivity and land degradation. By assessing past and actual trends the paper shows trajectories, impacts and implications for food security. The methodology may be useful to follow, in particular the analysis of the time series with focus on selected regions of Africa and case countries. Good methods and indicators definition to assess agriculture and yields gap as well as main land uses changes, drivers and effects such as land degradation and desertification. Nevertheless the data used in this study, only provide results and outputs aggregated at country/region; trends in HANPP are from 1980 to 2005.

Kessler J., 1994, Usefulness of the human carrying capacity concept in assessing ecological sustainability of land-use in semi-arid regions, Agriculture, Ecosystems and Environment 48: 273-284.

http://www.researchgate.net/publication/223866464_Usefulness_of_the_human_carrying_capacity_concept_in_assessing_ecological_sustainability_of_land-use_in_semi-arid_regions

Excellent pioneer work on carrying capacity in the Sahel, using statistics to compare actual condition and trend rates of exploitation of natural resources to assess sustainable land-use. Data and methods are outdated, but it is an interesting approach making use of limited statistical data.

Runnig S, 2014, A regional look at HANPP: human consumption is increasing, NPP is not, Environ. Res. Lett. 9 http://iopscience.iop.org/article/10.1088/1748-9326/9/11/111003/pdf.

Complementary critical paper with insights on how understand and to use best the study of Abdi et al (2014).

Van Ittersum et al. 2016. *Can sub-Saharan Africa feed itself? Proceedings of the National Academy of Sciences, 113(52), 14964-14969. doi: 10.1073/pnas.1610359113*

Up to date evaluation of future (by 2050) self-sufficiency in 10 key SSA countries which jointly account for 54% of the 2010 population and 58% of the 2010 arable land area in SSA. The analysis combines projection of the demand for the five main cereals (maize, millet, rice, sorghum, and wheat) and the possible supply. Future supply is estimated given crop land through various degrees of yield gap closure and other strategic options (e.g., expanded irrigation area, increased cropping intensity, and crop area expansion).

OTHER REFERENCES:

Erb, K.H.; Krausmann, F.; Gaube, V.; Gingrich, S.; Bondeau, A.; Fischer-Kowalski, M.; Haberl, H., 2009, Analyzing the global human appropriation of net primary production - processes, trajectories implications. An introduction. Ecological Economics 69, 250-259.

A global HANPP study much cited in works with a focus also on Western Africa.

Fiala N, 2008, Measuring sustainability: Why the ecological footprint is bad economics and bad environmental science, Ecological Economics, 6 7: 5 1 9 – 5 2 5.

Fischer G., H. van Velthuizen, M. Shah, F. Nachtergaele, 2002, Global Agro-ecological Assessment for Agriculture in the 21st Century: Methodology and Results, International Institute for Applied Systems Analysis, Food and Agriculture Organization of the United Nations.

Higgins et al., 1984, Capacité potentielle de charge démographique des terres du monde en développement. FAO.

Haberl, H., Erb, K., & Krausmann, F., 2013, Global human appropriation of net primary production (HANPP). Retrieved from http://www.eoearth.org/view/article/153031

Haberl H., H. Erb, F. Krausmann, V. Gaube et al, 2007, Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems, PNAS, vol. 104, no. 31.

D'Herbes J. M., Loireau M, 2008, Capacités de charge et usages multiples de l'espace et des ressources. http://horizon.documentation.ird.fr/exl-doc/pleins_textes/griseli/010013721.pdf

Running S., 2012, A Measurable Planetary Boundary for the Biosphere, SCIENCE, VOL 337.

Sayre N., 2008, The Genesis, History, and Limits of Carrying Capacity, Annals of the Association of American Geographers, 98:1, 120- 134. http://dx.doi.org/10.1080/00045600701734356.

Vitousek P., H. Mooney, J. Lubchenco, J. Melillo, 1997, Human Domination of Earth's Ecosystems, SCIENCE VOL. 277 (494-499).

Zhang Y., M. Xu, H. Chen, J. Adams, 2009, Global pattern of NPP to GPP ratio derived from MODIS data: effects of ecosystem type, geographical location and climate, Global Ecology and Biogeography, 18, 280–290.

Review on key trends for SSA and particularly for the Sahel

Applied studies to assess actual, past and future trends of carrying capacity, NPP and HANPP in SSA and the Sahel.

KEY REFERENCES:

Abdi et al. (2014), Ardö (2015, Fetzel et al.(2012): see previous citations.

Africa Progress Panel, 2014, Grain, Fish and Money: Financing Africa's Green and Blue Revolutions, AFRICA PROGRESS REPORT 2014.

http://app-cdn.acwupload.co.uk/wp-content/uploads/2014/05/APP_APR2014_24june.pdf

The best and most recent multi-stakeholders approach about development in Africa, updated every year around a specific theme. Essential in the assessment and modelling of agriculture, carrying capacity and HANPP, as well to identify main drivers, socioeconomic contexts and scenarios narratives; a key text to have both the "north" and "south" perspectives about Africa.

Banque africaine de développement (BAD) and WWF, 2012, Rapport sur l'empreinte écologique de l'Afrique.

http://d2ouvy59p0dg6k.cloudfront.net/downloads/africa_efr_french_high_res.pdf

The best attempt to convert complex data into usable information to assess carrying capacity; however not all information is spatially explicit; hence there are limitations in its use for real planning and assessments. The report assesses the actual carrying capacity and trends in resource use patterns. Also pathways and trajectories for the implementation of green development for Africa are assessed.

Blein R., B. Soule, B. Faivre Dupaigre, B. Yerima, 2008, Agricultural Potential of West Africa (ECOWAS), FRAM, France. http://www.fondation-farm.org/zoe/doc/potentialites_rapport_ang_mp.pdf

The best available report on agriculture and rural development for West Africa, including socioeconomic and technological assessments, as well as forecast scenarios and spatial analysis, key for estimating actual and future trends on carrying capacity and main drivers for scenarios and modelling.

Jalloh, A. et al (Editors), 2013, West African Agriculture and Climate Change: A Comprehensive Analysis, IFPRI, CCAFS.

http://ebrary.ifpri.org/utils/getdownloaditem/collection/p15738coll2/id/127444/filename/127655.pdf/mapsto/pdf/type/singleitem

The most complete study on agriculture, rural development, technologies and climate change for West Africa, useful to assess future trends in carrying capacity but limited in terms of the drivers used, scenarios perspective and dynamics.

Zica M., Erb K, 2009, The global loss of net primary production resulting from human-induced soil degradation in drylands, Ecological Economics 69 (2009) 310–318.

This study, already cited for its methodological contribution, also presents a global estimate of net primary production (NPP) losses caused by human-induced dryland degradation, including SSA and the Sahel. The results reveal that the contribution of land degradation to the total HANPP in drylands is comparable to that of the overall annual socioeconomic biomass harvest. The findings can be used to assess trends in land use change and identify strategies aimed at reducing dryland degradation as an option to sustain future population numbers without placing further pressures on dryland ecosystems.

Applied studies to assess agricultural trends (actual, past and future) in SSA and Sahel.

Lambin E., S. D'Haen, O. Mertz, J. Østergaard Nielsen & K. Rasmussen, 2014, Scenarios on future land changes in the West African Sahel, Geografisk Tidsskrift - Danish Journal of Geography, 114:1, 76-83, DOI: 10.1080/00167223.2013.878229.

http://www.tandfonline.com/doi/pdf/10.1080/00167223.2013.878229

Ringler, C., Cenacchi, N., Koo, J., Robertson, R. D., Fisher, M., Cox, C. M., Rosegrant, M. W., 2014, Sustainable agricultural intensification: The promise of innovative farming practices. In A. Marble, & H. Fritschel (Eds.), 2013 global food policy report (pp. 43-52). Washington, D.C.: International Food Policy Research Institute (IFPRI).

http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/128047

Ramirez-Villegas J., Thornton PK, 2015, Climate change impacts on African crop production. CCAFS Working Paper no. 119. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Copenhagen, Denmark.

https://ccafs.cgiar.org/publications/climate-change-impacts-african-crop-production#.Vgqx4C6qpBc

WRI, 2013, Creating a Sustainable Food Future.

http://www.wri.org/sites/default/files/wri13_report_4c_wrr_online.pdf

Global and regional (cases studies) agriculture, rural development and food production/consumption entry point.

WWF and UNEP, 2014, African ecological futures: Synthesis paper.

http://www.unep.org/roa/Portals/137/AMCEN15Docs/African%20Ecological%20Futures_Synthesis%20Paper.pdf

Complete assessment of environmental drivers, impacts and trends for Africa (with cases studies).

OTHER REFERENCES:

African Development Bank, 2011, Africa in 50 Years' Time scenarios.

http://www.afdb.org/fileadmin/uploads/afdb/Documents/Publications/Africa%20in%2050%20Years%20Time.pdf

The most complete macroeconomic and scenarios development study for Africa; to be used as input for the scenarios narratives and drivers.

AGRA, 2014, Africa Agriculture Status Report 2014: CLIMATE CHANGE AND SMALLHOLDER AGRICULTURE IN SUB-SAHARAN AFRICA, AGRA, Nairobi, Kenya.

Agriculture, climate change and small holder's entry point.

Alexandratos, N., and J. Bruinsma. 2012. World agriculture towards 2030/2050: The 2012 revision. Rome: Food and Agriculture Organization of the United Nations (FAO).

http://www.fao.org/docrep/016/ap106e/ap106e.pdf

(Agriculture entry point).

Banque Mondiale, 2008, Rapport sur le développement dans le monde. L'agriculture au service du développement, Banque mondiale Washington (DC).

https://openknowledge.worldbank.org/bitstream/handle/10986/5990/WDR%202008%20Overview%20Fr.pdf?sequence=4 (Agriculture and rural development entry point).

CIRAD and INRA, 2010, Agrimonde. Scénarios et défis pour nourrir le monde en 2050. Versailles, Ed. Quae

(Agriculture production/ consumption entry point).

Ericksen P, Thornton P, Notenbaert A, Cramer L, Jones P, Herrero M. 2011. Mapping "hot spots" of climate change and food insecurity in the global tropics. CCAFS Report no. 5. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Copenhagen, Denmark. https://cgspace.cgiar.org/rest/bitstreams/15510/retrieve

Garrity, D. P., Akinnifesi, F. K., Ajayi, O. C., Weldesemayat, S. G., Mowo, J. G., Kalinganire, A., Bayala, J., 2010, Evergreen agriculture: A robust approach to sustainable food security in Africa. Food Security, 2, 197-214. doi:10.1007/s12571-010-0070-7

http://link.springer.com/article/10.1007%2Fs12571-010-0070-7#page-1

Padgham J. et al., 2015, Vulnerability and Adaptation to Climate Change in the Semi-Arid Regions of West Africa, CARIAA ASSAR, ASSAR Working Papers

http://community.eldis.org/.5c62b3ea

Sultan B., 2015, Quels scénarios pour l'agriculture sous l'effet du réchauffement ? Conference ESCAPE : Les sociétés rurales face aux changements environnementaux en Afrique de l'Ouest, Project ESCAPE. https://skyros.locean-ipsl.upmc.fr/~ESCAPE/Sultan2.pdf

Thornton PK, Boone RB, J Ramirez-Villegas 2015. Climate change impacts on livestock. CCAFS Working Paper no. 120. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Copenhagen, Denmark. https://ccafs.cgiar.org/blog/climate-change-impacts-livestock-what-do-we-know#.Vgq0CC6qpBc

Vervoort, J. and Ericksen, P. 2012. No foresight, no food? Regional scenarios for Africa and South Asia. The Futures of Agriculture. Brief No. 03 - English. Rome: Global Forum on Agricultural Research (GFAR).

https://ccafs.cgiar.org/publications/no-foresight-no-food-regional-scenarios-africa-and-south-asia#.Vgq0LS6qpBc

World Bank, 2013, Transformer l'agriculture au Sahel comment y parvenir?

http://www.worldbank.org/content/dam/Worldbank/document/Africa/transforming-agriculture-in-the-sahel-background-note-french.pdf

WRI in collaboration with UNDP, UNEP, and World Bank., 2008, Turning back the desert: How farmers have transformed Niger's landscape and livelihoods. World resources 2008: Roots of Resilience. Growing the wealth of the poor (pp. 142-157). Washington, DC: WRI.

ANNEX II. References on a number of spatial data layer used

GAEZ agro-ecological suitability and productivity

The GAEZ database v.3 (http://gaez.fao.org/Main.html#) has developed, among others, a "agro-ecological suitability and productivity" product. This is evolved from previous work on AEZ and provides a crop specific evaluation based on crop growth models.[41] Within this product we are specifically looking at the Crop Suitability classes. These are defined by GAEZ per crop, per water regime (rainfed, irrigation) and per input level (low, intermediate and high). Moreover one can select a climate baseline (1961-90) or among several climate scenarios. The output of the query on the GAEZ database comes as GeoTIFF with a resolution of 5 arc-minute grid, or 10 x 10 km at the Equator, thus equivalent to the MapSPAM grid. The table below gives the complete list of crops and management levels used (a sub-set relevant for the Sahel countries out of a broader set of crops/input levels provided in GAEZ). It is a total of 12 (4 irrigated and 8 rainfed) crops and a total of 35 combinations crops/ input levels.

Table 17 Selected suitability crops and management levels

			Rainfed			**Irrigated**	
Crop groups	**Reference crop**	**suffix**	**High input**	**Interm. Input**	**Low input**	**High input**	**Interm. Input**
Cereals	Wetland rice	Rcw	-	-	-	X	X
	Maize	Mai	X	X	X	X	X
	Millet	Pml	X	X	X		
	Sorghum	Srg	X	X	X	-	-
Root-tubers							
	Cassava	Csv	X	X	X	-	-
	Yam	Yam	X	X	X	-	-
Sugar crops	Sugarcane	Suc	X	X	X	X	X
Pulses	Bean (Phaseolus)	Phb	X	X	X	-	-
Vegetables	Onion	Oni	-	-	-	X	X
Oil crops							
	Groundnut	Grd	X	X	X	-	-
Fibre crops	Cotton	Cot	X	X	X	-	-

Source: IIASA andFAO (2012)

[41]For more details: http://www.fao.org/fileadmin/user_upload/gaez/docs/GAEZ_Model_Documentation.pdf .

Gridded Livestock of the World

Below the Gridded Livestock of the World [42] (GLW version 2.01) and specifically the layer for cattle density (expressed as animals counts per square kilometer) is portrayed, with highlighted the Sahelian countries under study:

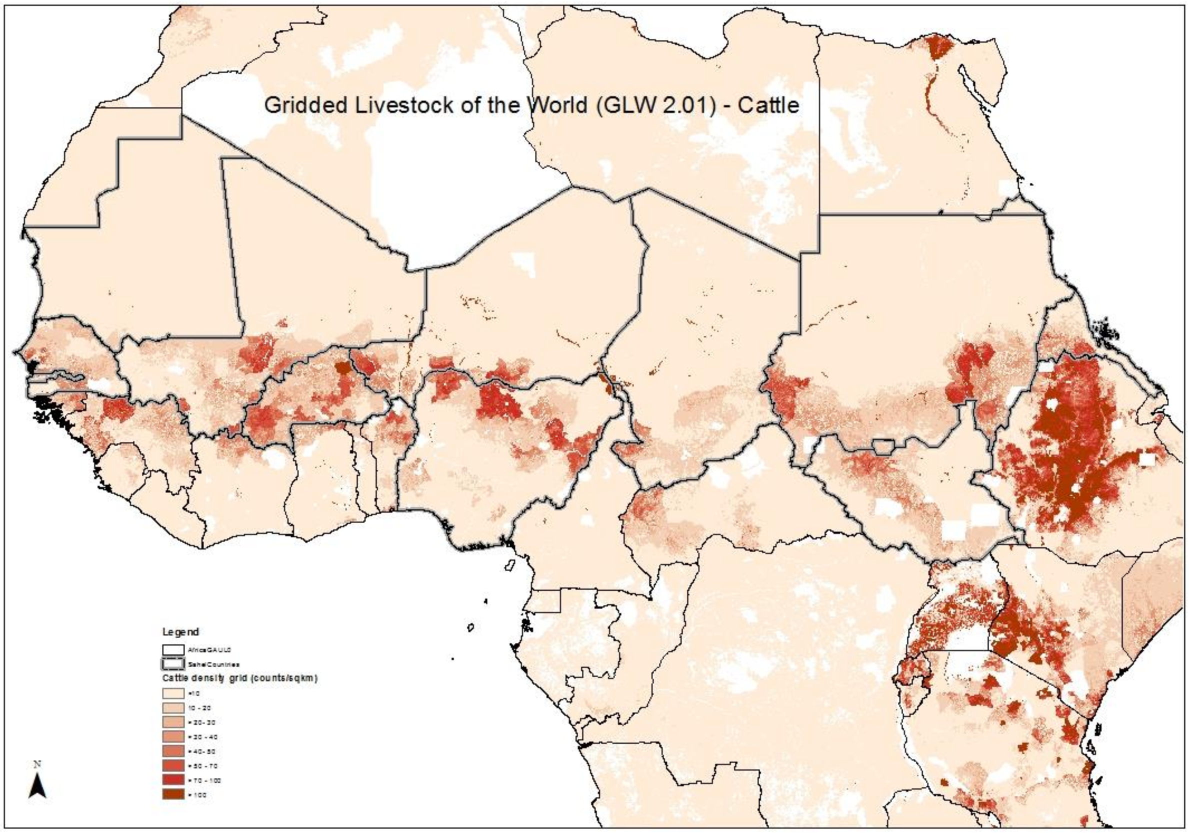


Figure 19 Livestock (cattle) grid

Source: Own elaboration based on FAO data updated by Robinson et al . (2014)

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[42] Gridded livestock of the world, Africa Model of Cattle density, 2010 with a resolution of 3 minutes of arc (around 5,6 km at the equator) http://www.fao.org/geonetwork/srv/en/metadata.show?id=47949&currTab=distribution

Agro-Ecological Zones

Agro-ecological Zones are used for final reporting of the NNP values. The map below shows the AEZ classification according to the FAO/IIASA methodology. The spatial dataset was elaborated by IFPRI/HarvestChoice, 2014.[43]

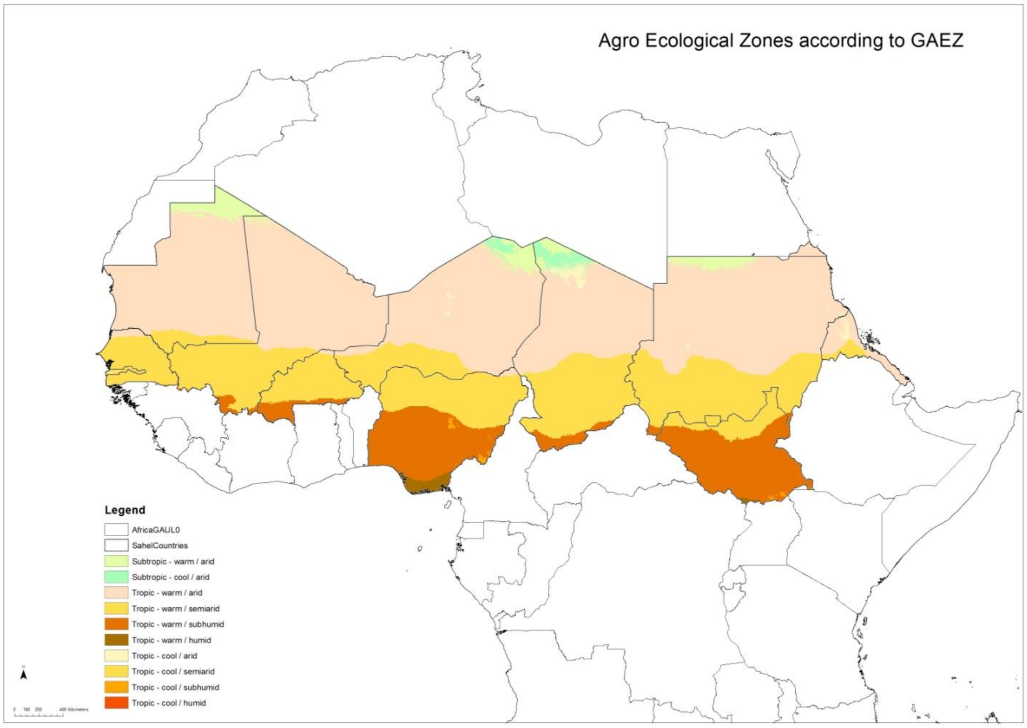

Figure 20 Agro Ecological Zones (GAEZ 16 Classes)

Source: IFPRI –HarvestChoice (2014)

The classification is originally based on 16 classes although only 10 are occurring in the area of study. AEZs are geographical areas exhibiting similar climatic conditions that determine their ability to support rainfed agriculture. At a regional scale, AEZs are influenced by latitude, elevation, and temperature, as well as seasonality, rainfall amounts and distribution during the growing season. The resulting AEZ classifications for Africa have three dimensions: major climate zone (tropics or subtropics), moisture zones (water availability: arid, semi-arid, humid, sub-humid) and highland/lowland (warm or cool based on elevation).

Table 18 AEZ of the studied area

211	Sub-tropic - warm / arid	314	Tropic - warm / humid
221	Sub-tropic - warm / semiarid	321	Tropic - cool / arid
311	Tropic - warm / arid	322	Tropic - cool / semiarid
312	Tropic - warm / semiarid	323	Tropic - cool / sub-humid
313	Tropic - warm / sub-humid	324	Tropic - cool / humid.

Source: Adapted from Source: IFPRI –HarvestChoice (2014)

[43] AEZ (16-class, 2009). International Food Policy Research Institute, Washington, DC., and University of Minnesota, St. Paul, MN. Available online at http://harvestchoice.org/data/aez16_code

Appendix III: Diagrams of procedures used in the analysis

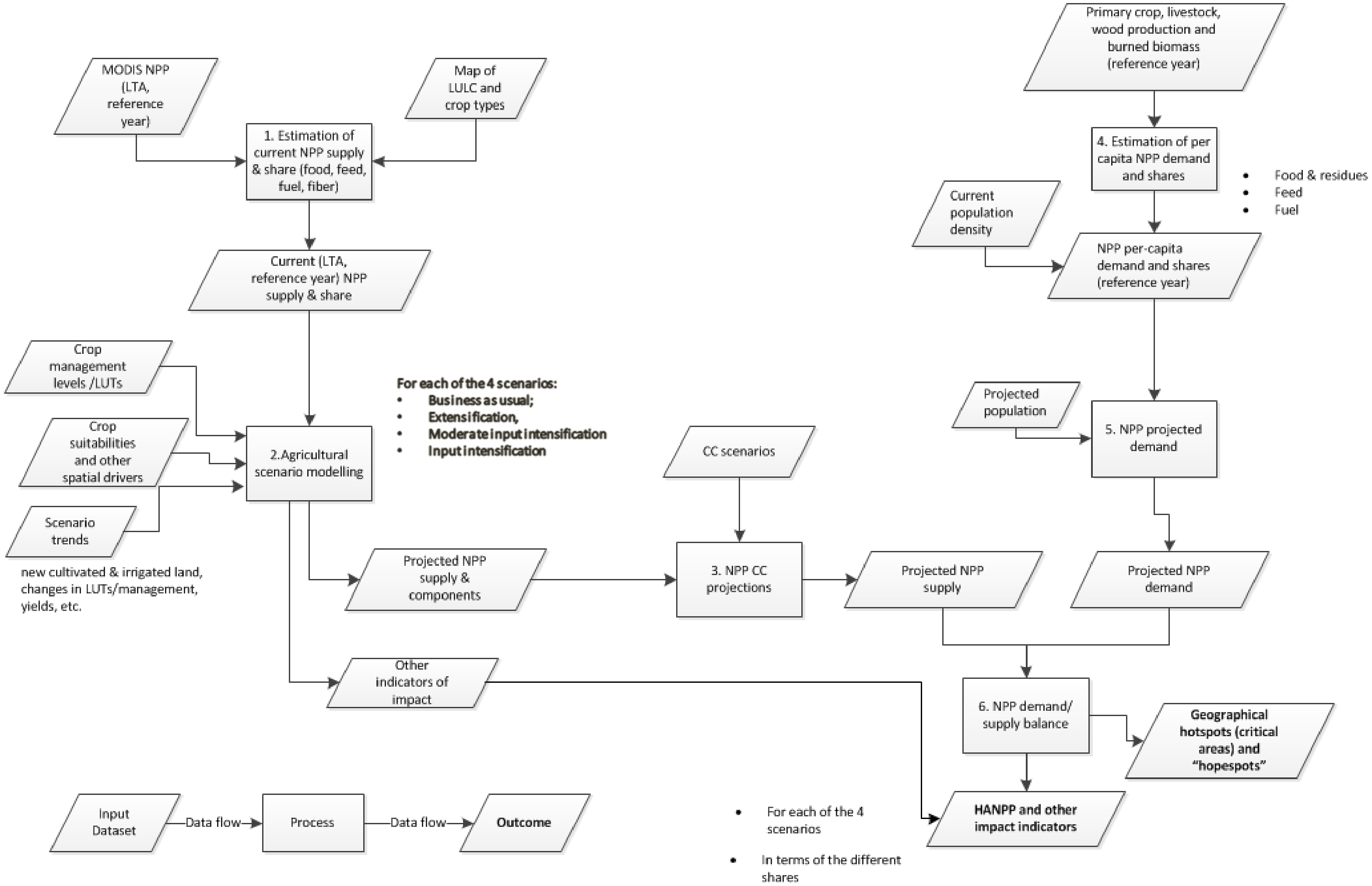

Figure 21 workflow of the modelling procedures (Top level)

Source: Own elaboration

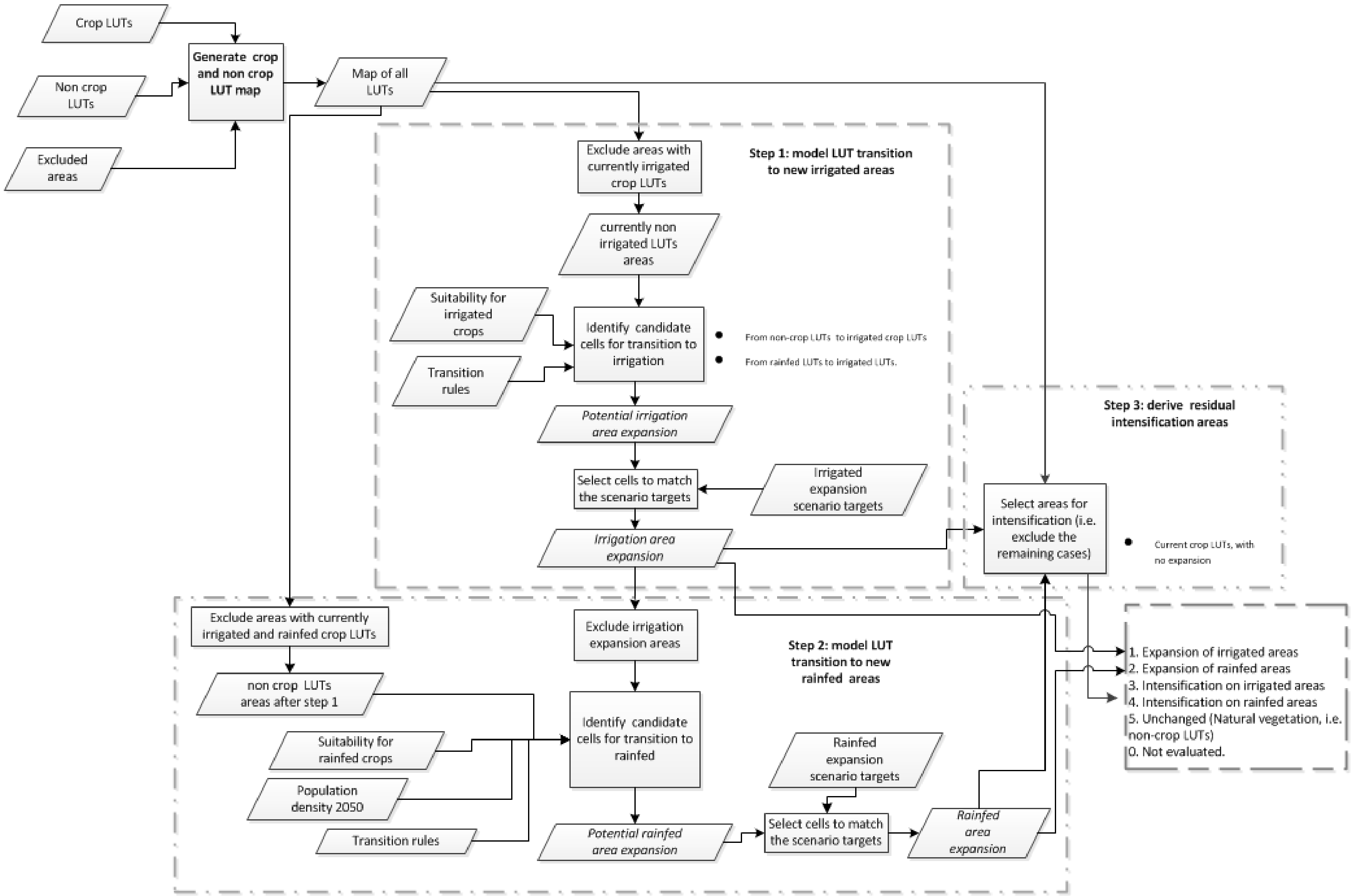

Figure 22 Workflow of the spatial allocation procedure (NPP supply)
Source: Own elaboration

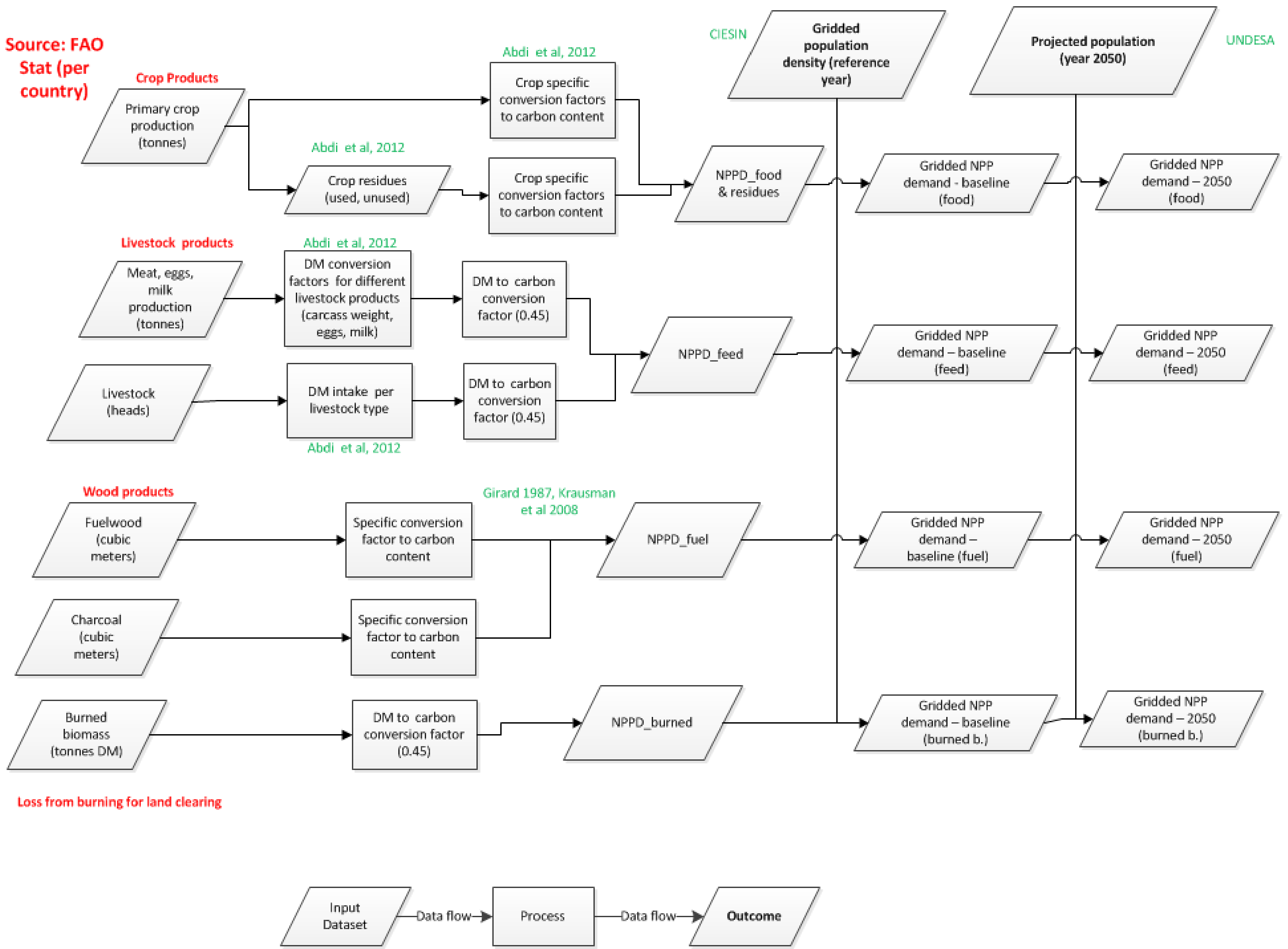

Figure 23 Workflow of the modelling procedures (NPP demand) Source: Own elaboration

Appendix IV: Map of Land Utilisation Types (LUTs)

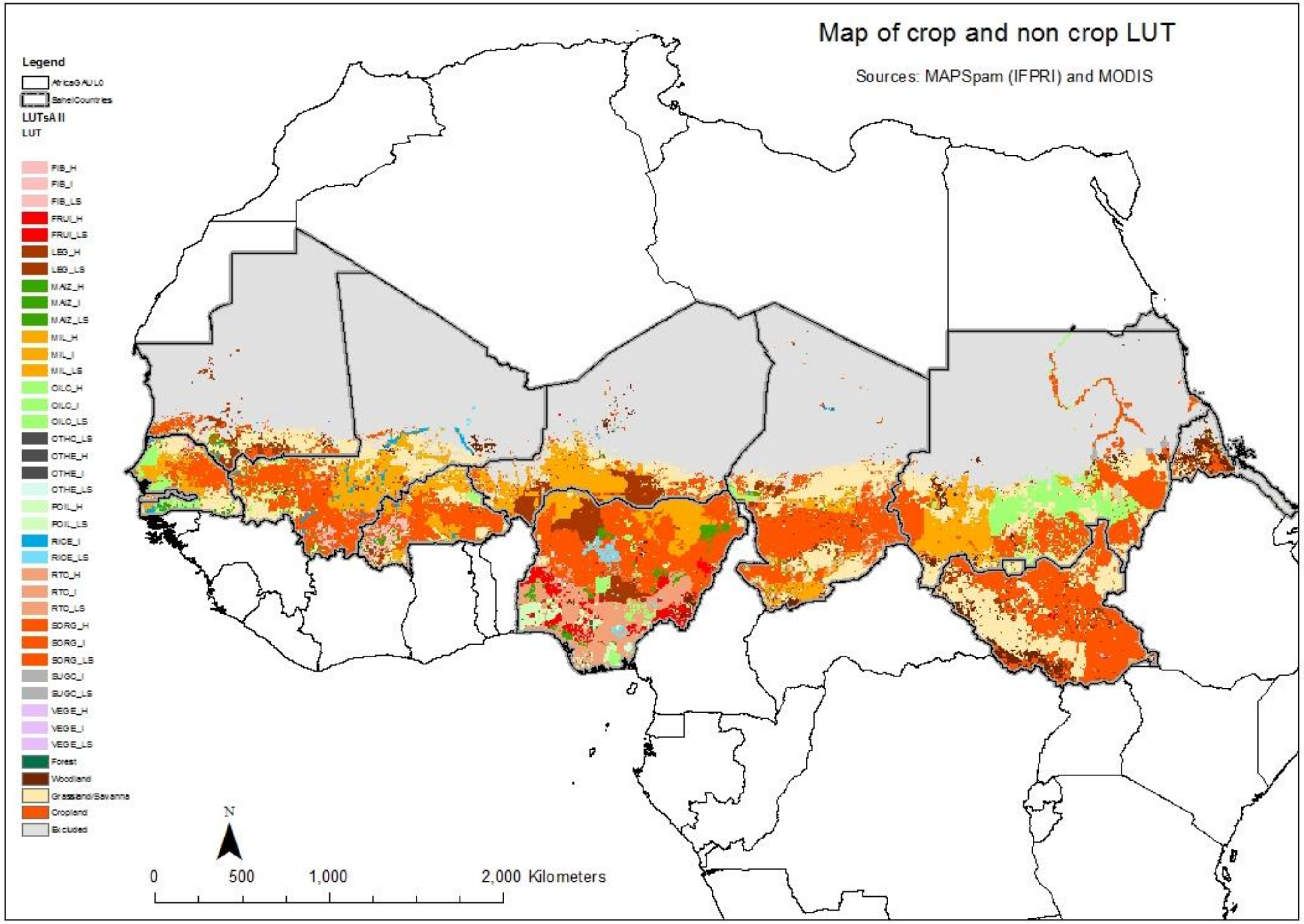

Figure 24 Map of Land Utilization Types (LUTs)

Source: IFPRI –HarvestChoice (2014)

Appendix V: Map of LUT transitions (with examples for 2 scenarios)

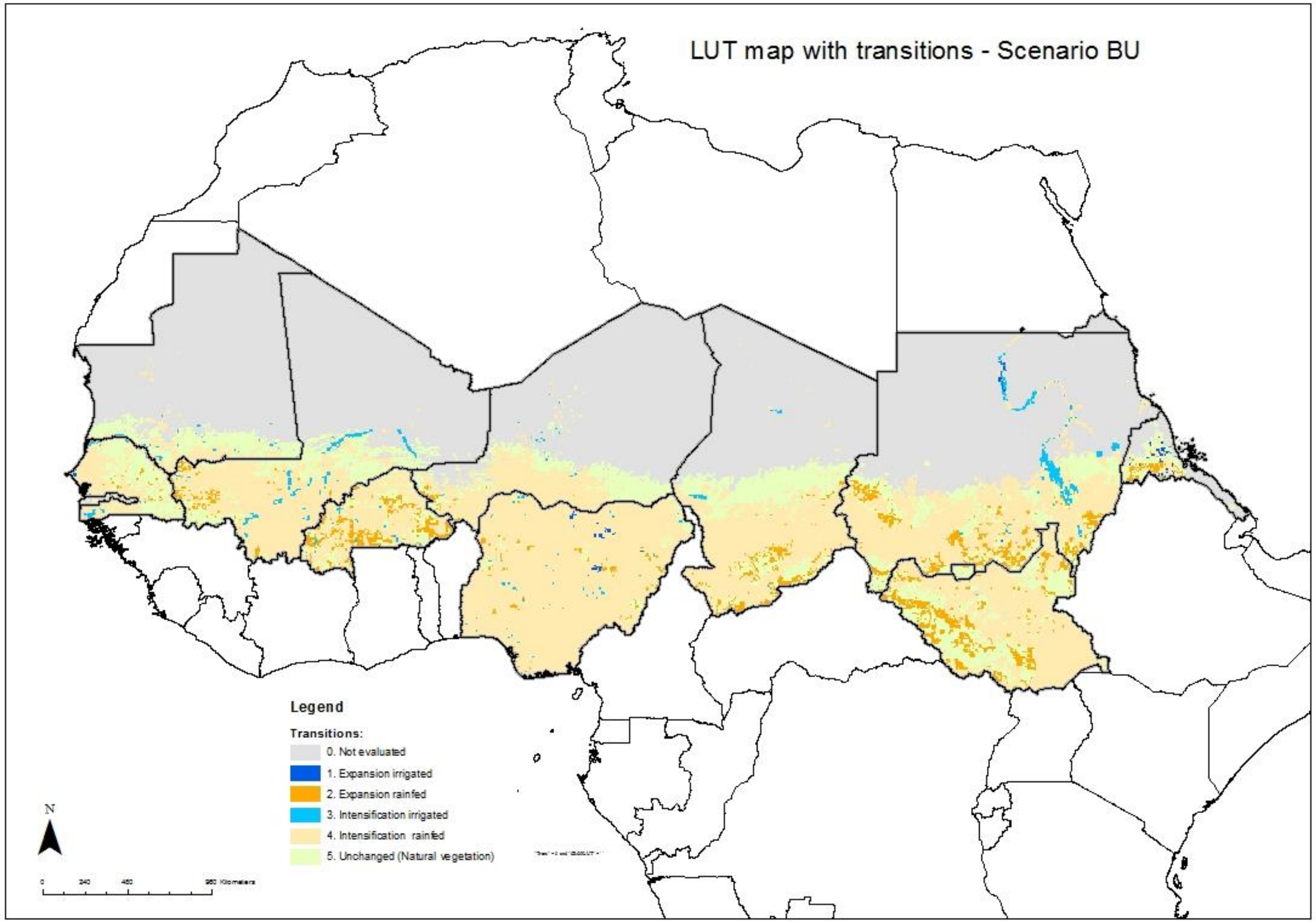

Figure 25 Map of LUTs transitions – BU scenario
Source: Own elaboration

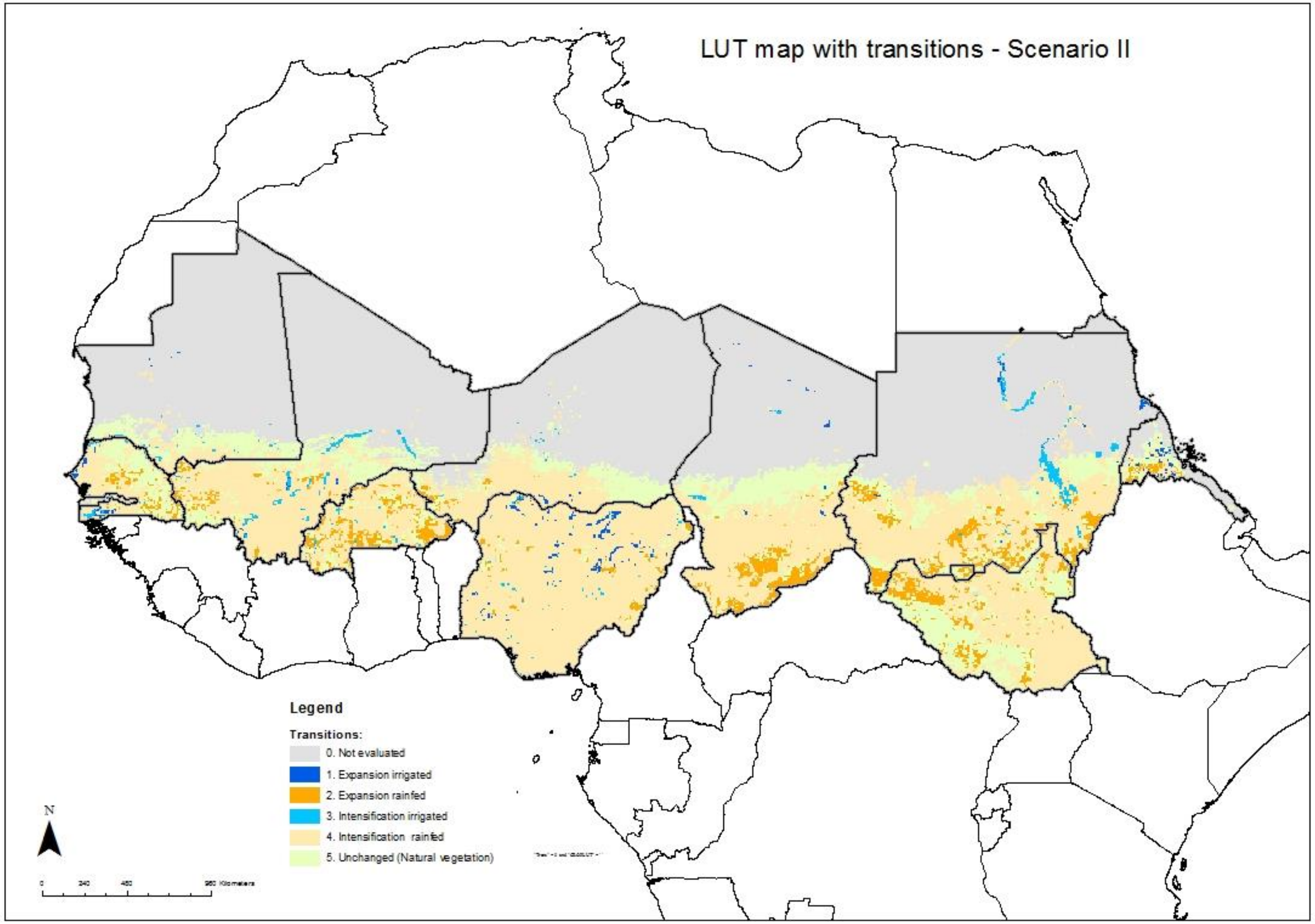

Figure 26 Map of LUTs transitions – II scenario
Source: Own elaboration

Appendix VI: Maps of HANPP, "hot spots" and "hope spots"

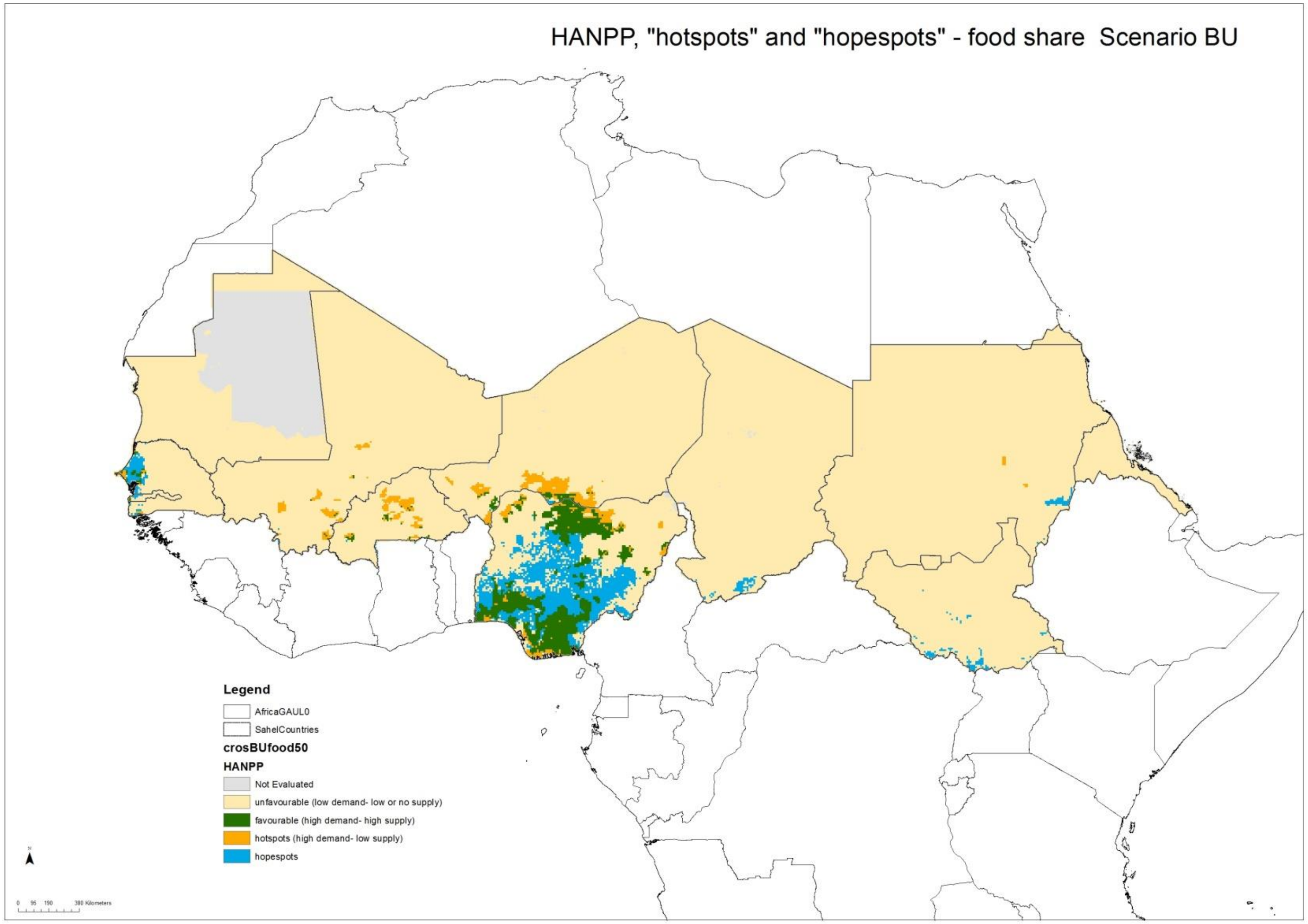

Figure 27 Map of "Hot spots" and "hope spots" – BU scenario, food share
Source: Own elaboration

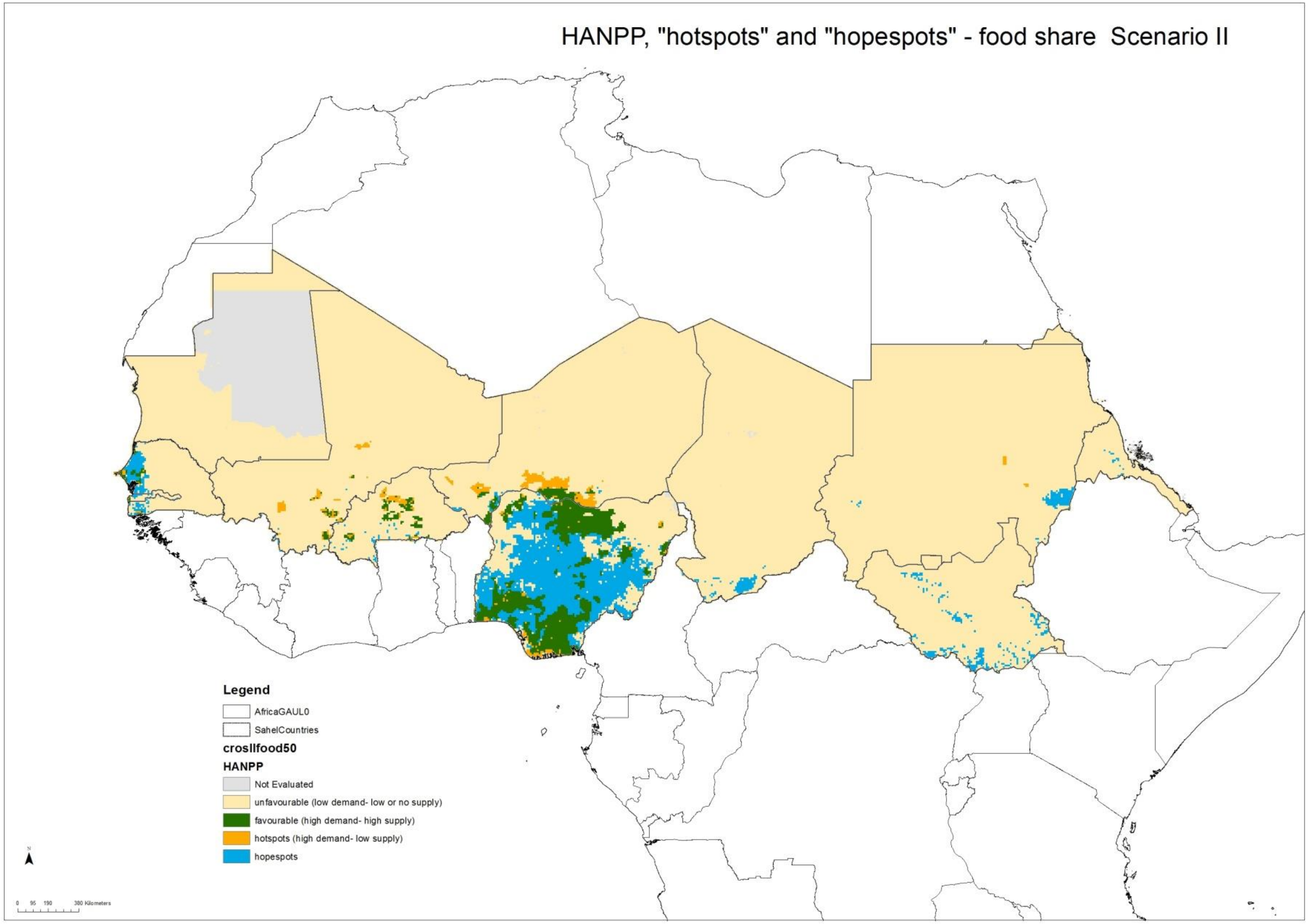

Figure 28 Map of "Hot spots" and "hope spots" – II scenario, food share
Source: Own elaboration

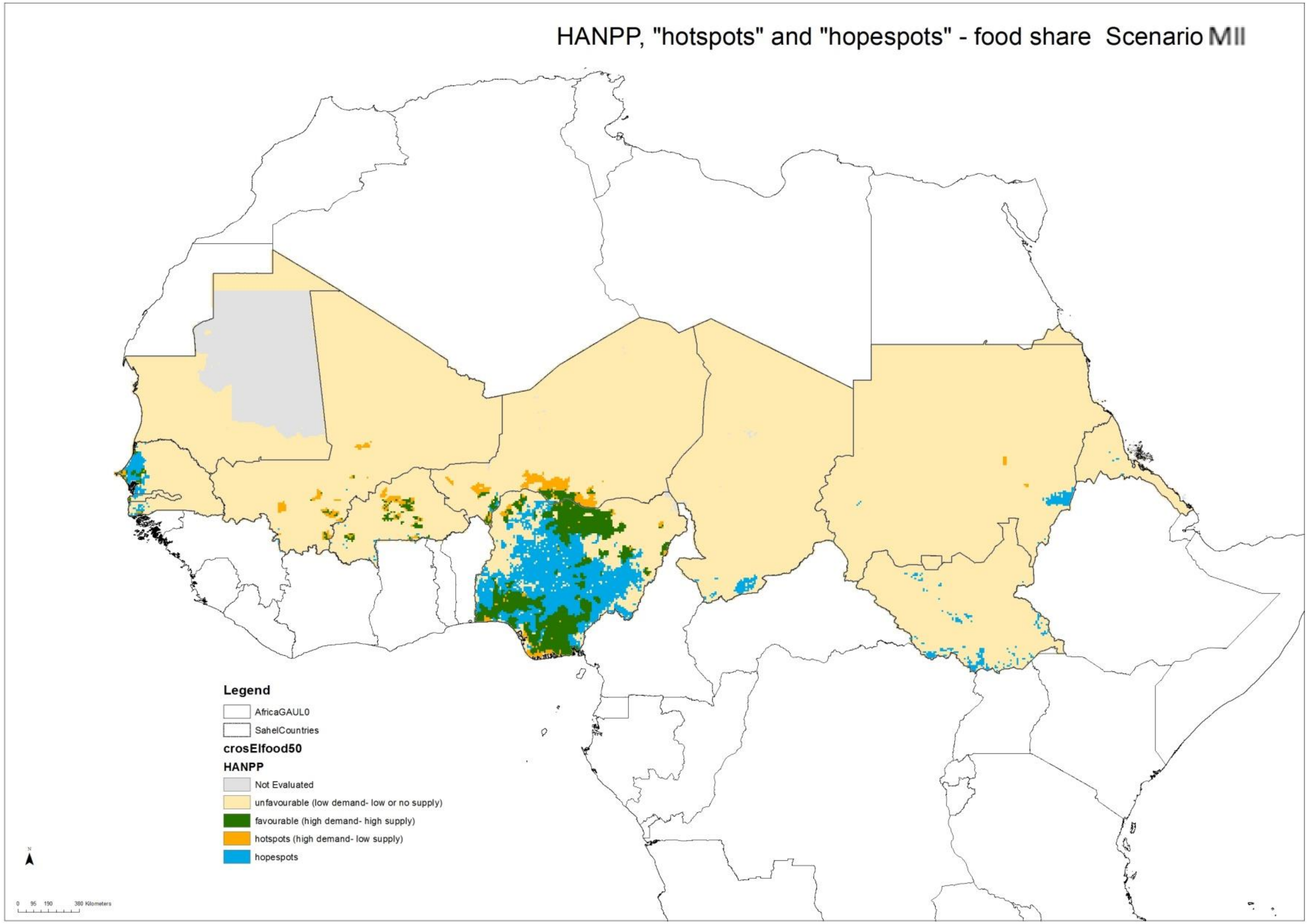

Figure 29 Map of "Hot spots" and "hope spots" – MII scenario, food share
Source: Own elaboration

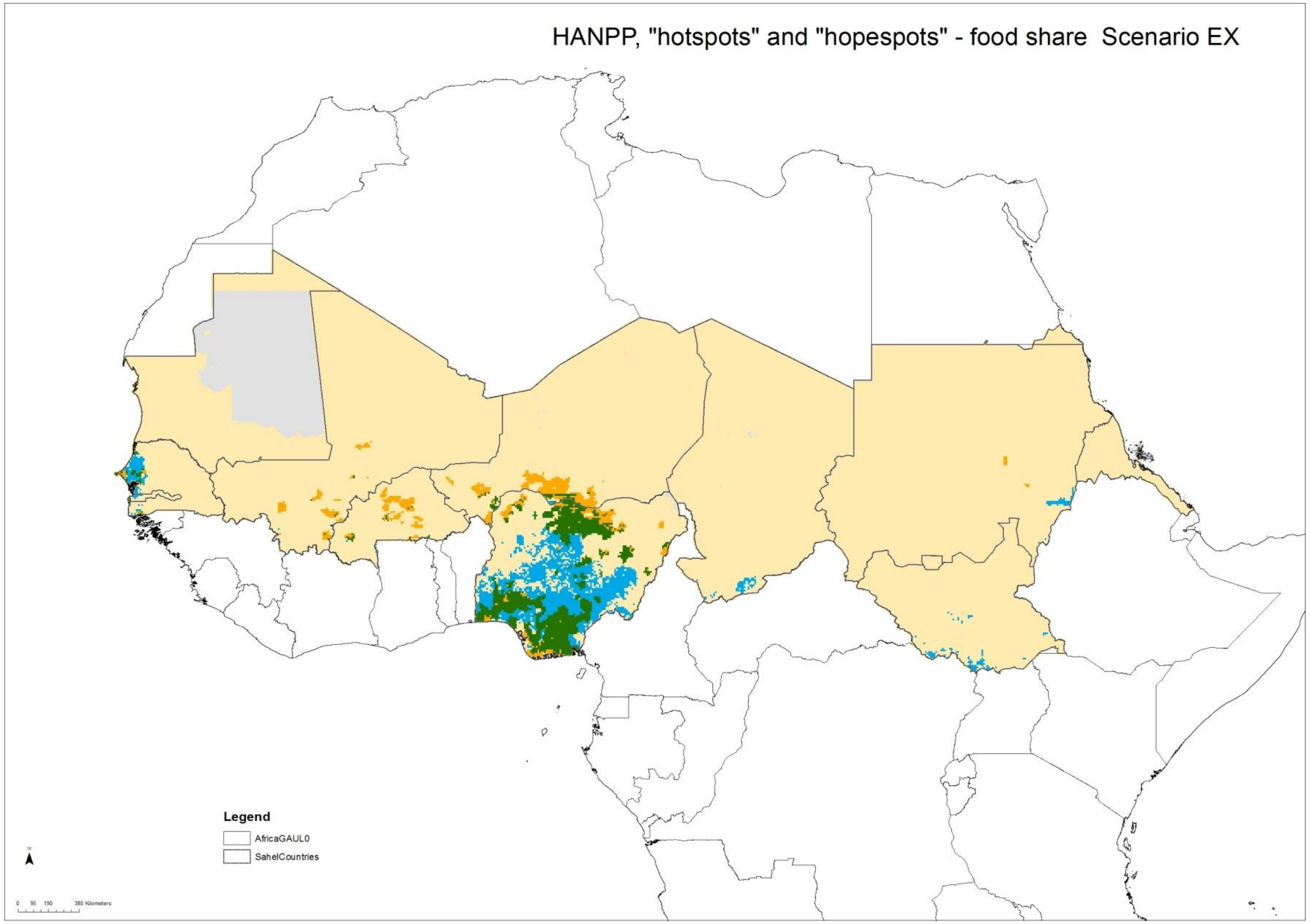

Figure 30 Map of "Hot spots" and "hope spots" – EX scenario, food share
Source: Own elaboration

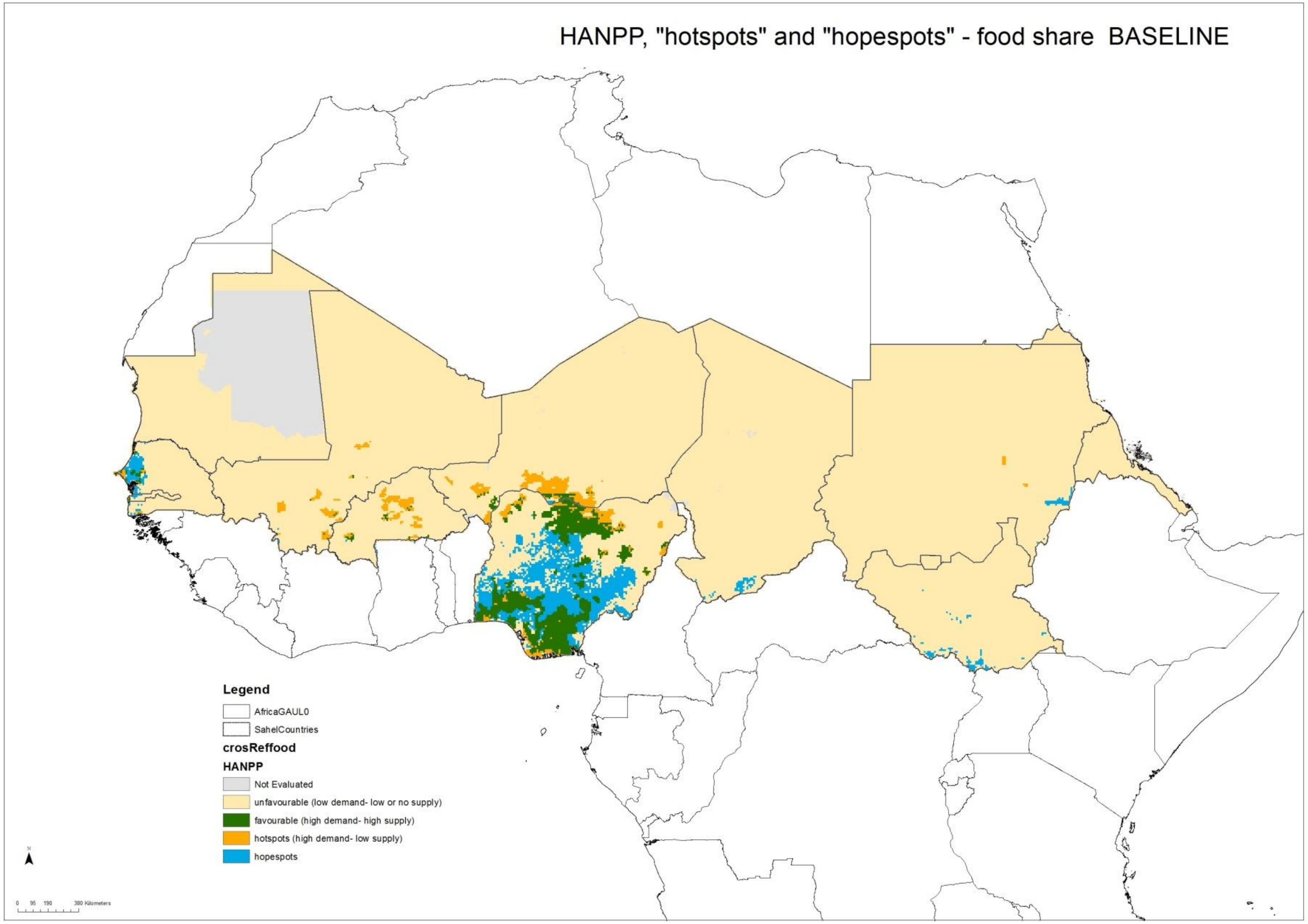

Figure 31 Map of "Hot spots" and "hope spots" – Baseline, food share
Source: Own elaboration

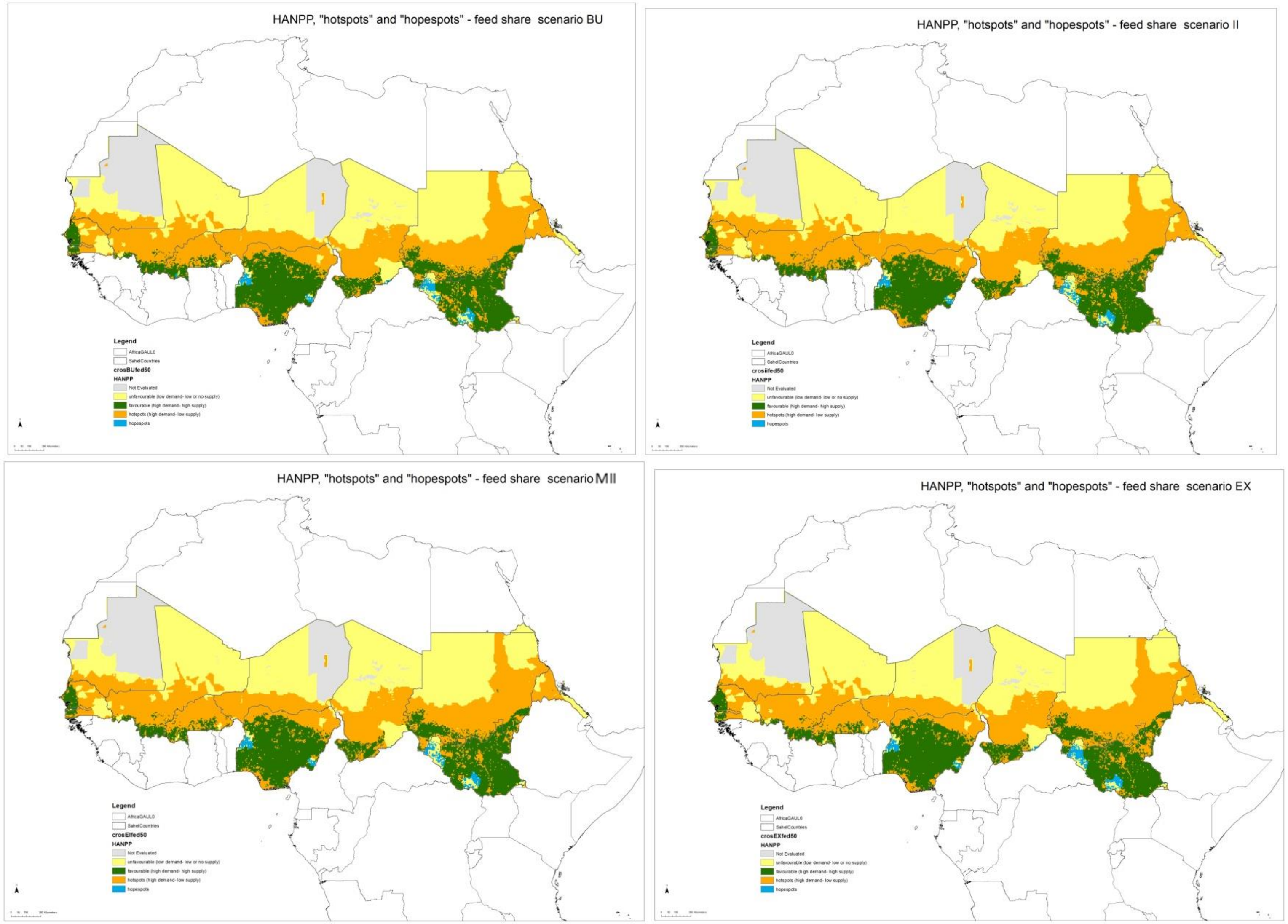

Figure 32 Map of "Hot spots" and "hope spots" – all scenarios, feed share.
Source: Own elaboration

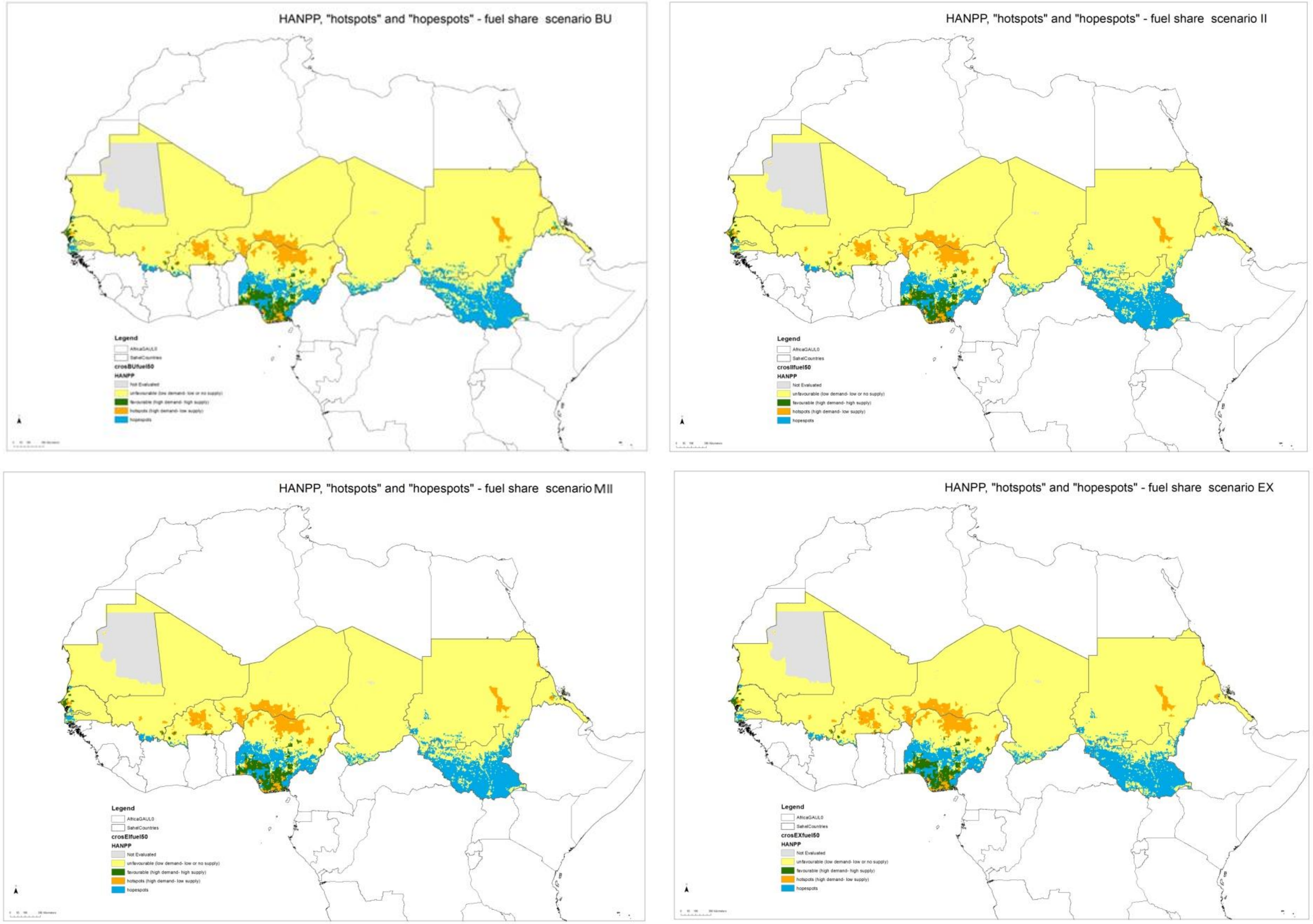

Figure 33 Map of "Hot spots" and "hope spots" – all scenarios, fuel share.
Source: Own elaboration

Appendix VI: Maps of livestock "hot spots" and "hope spots"

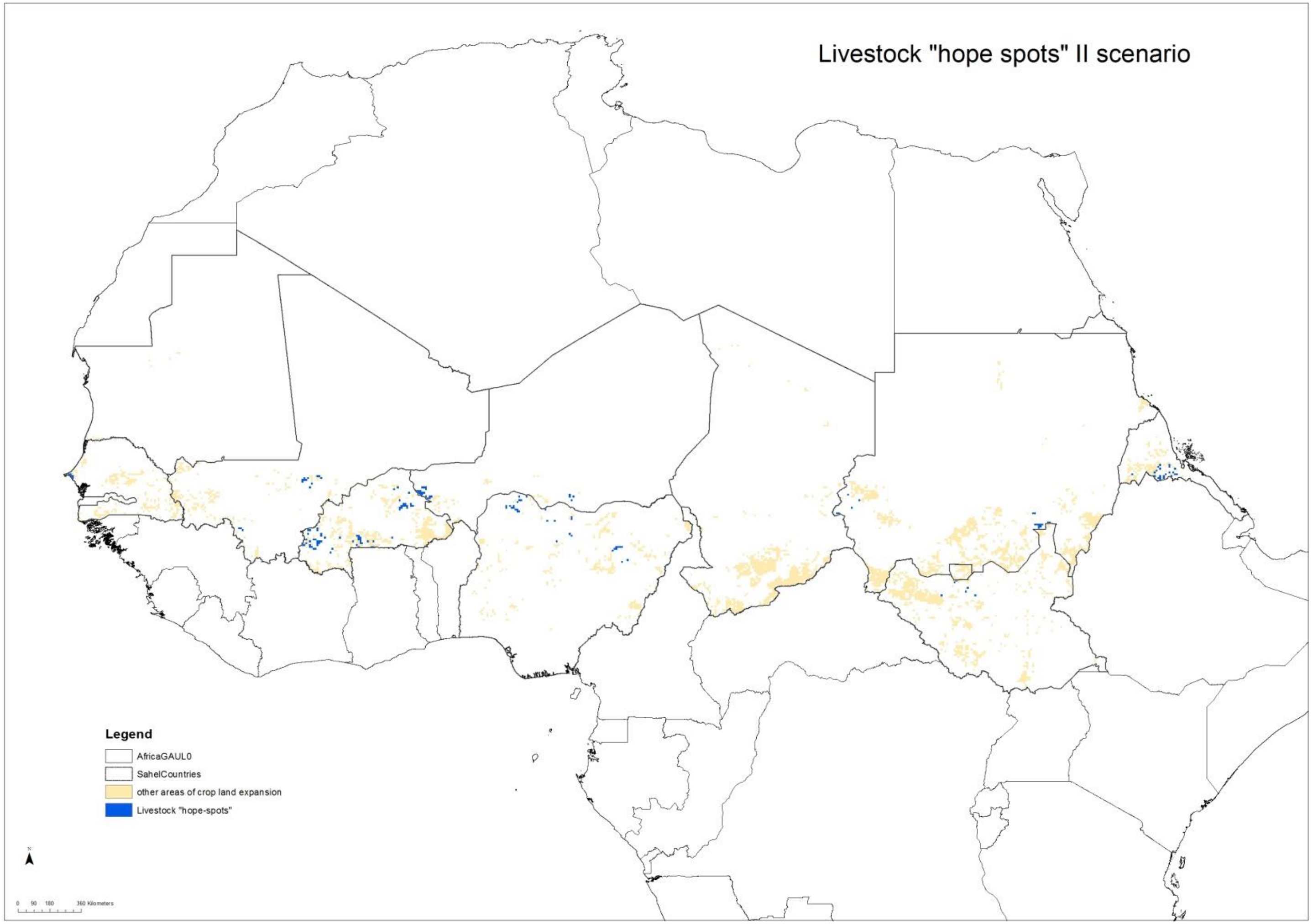

Figure 34 Map of livestock "hope spots" –II scenario
Source: Own elaboration

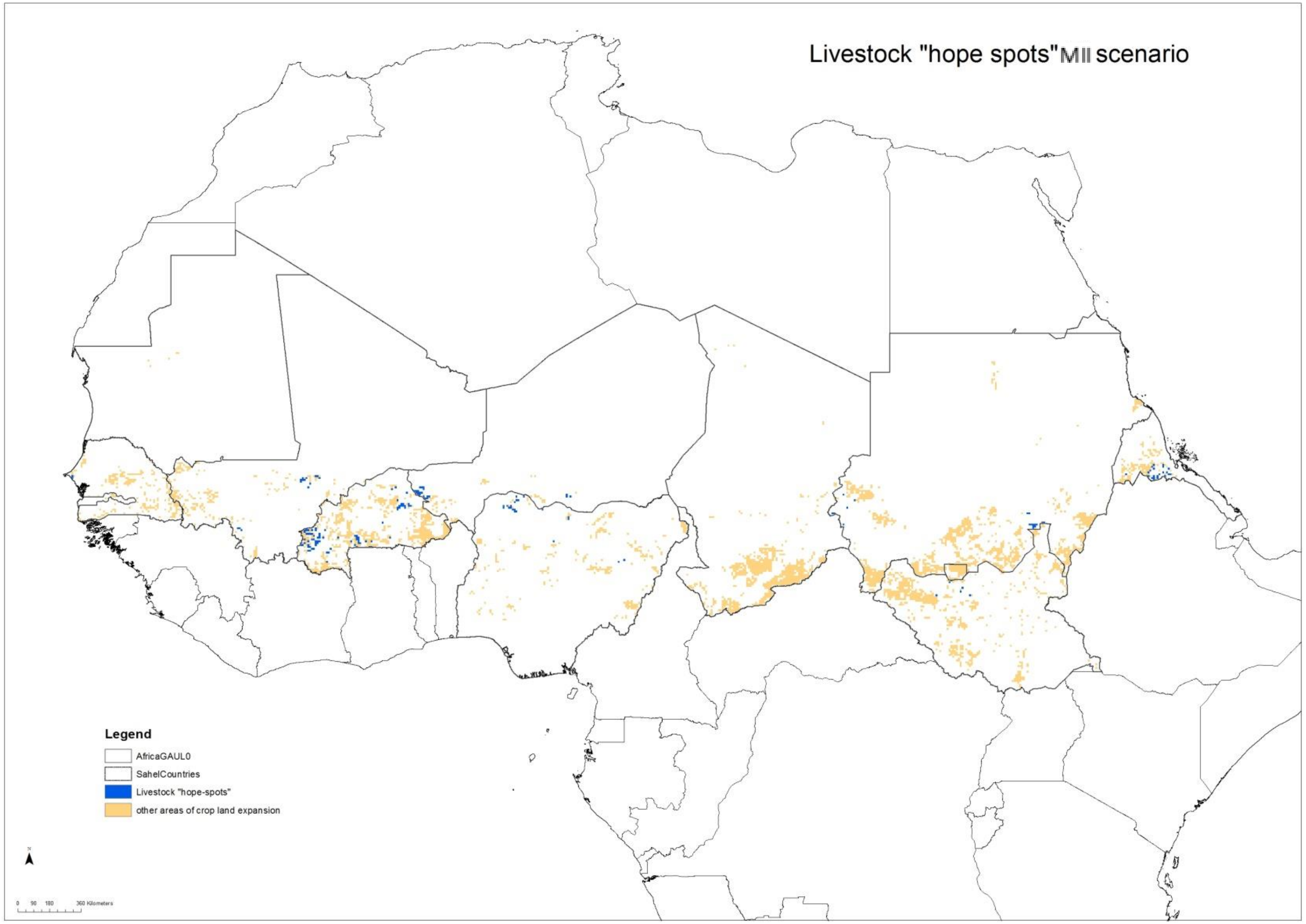

Figure 35 Map of livestock "hope spots" – MII scenario
Source: Own elaboration

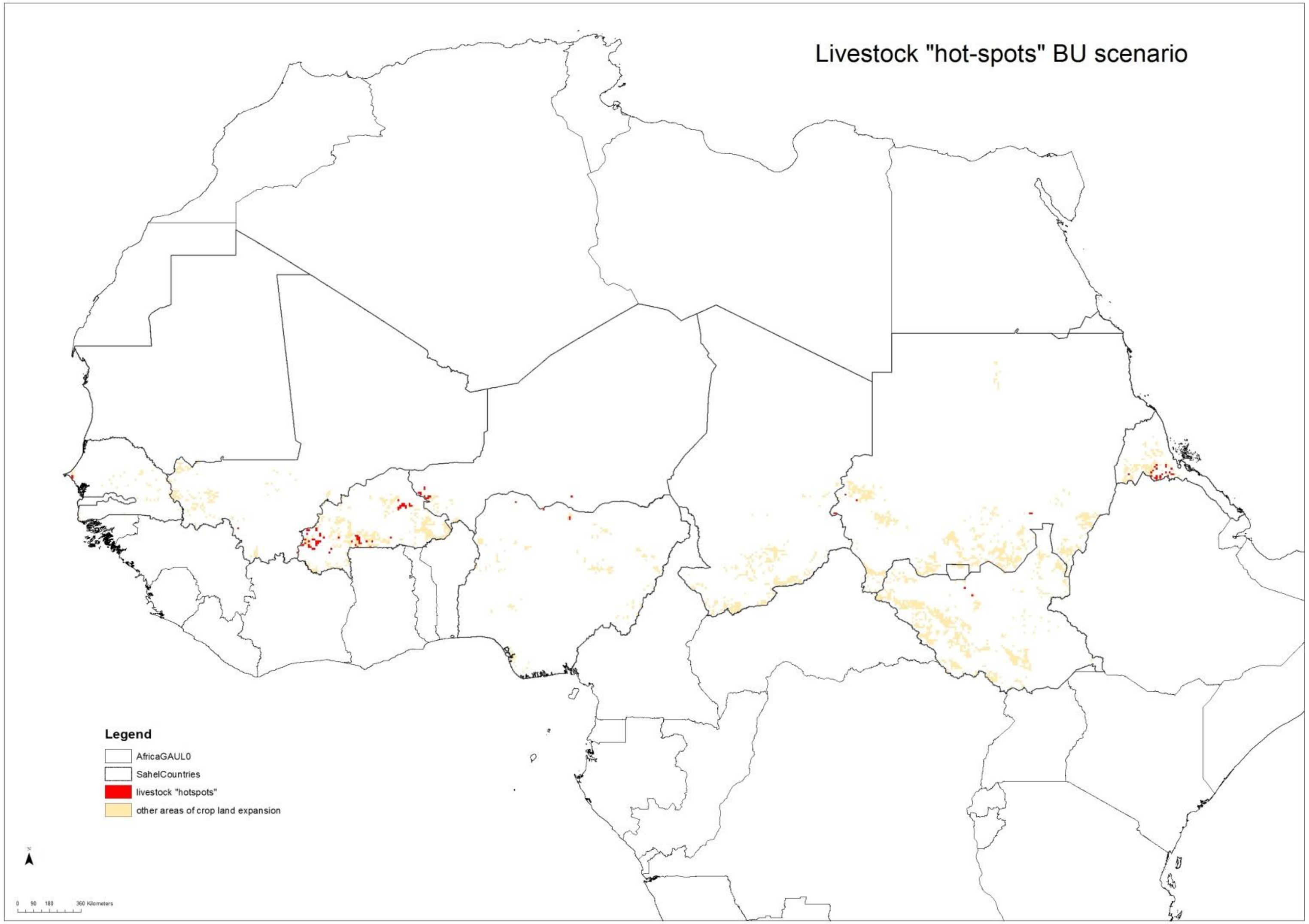

Figure 36 Map of livestock "hot spots" – BU scenario
Source: Own elaboration

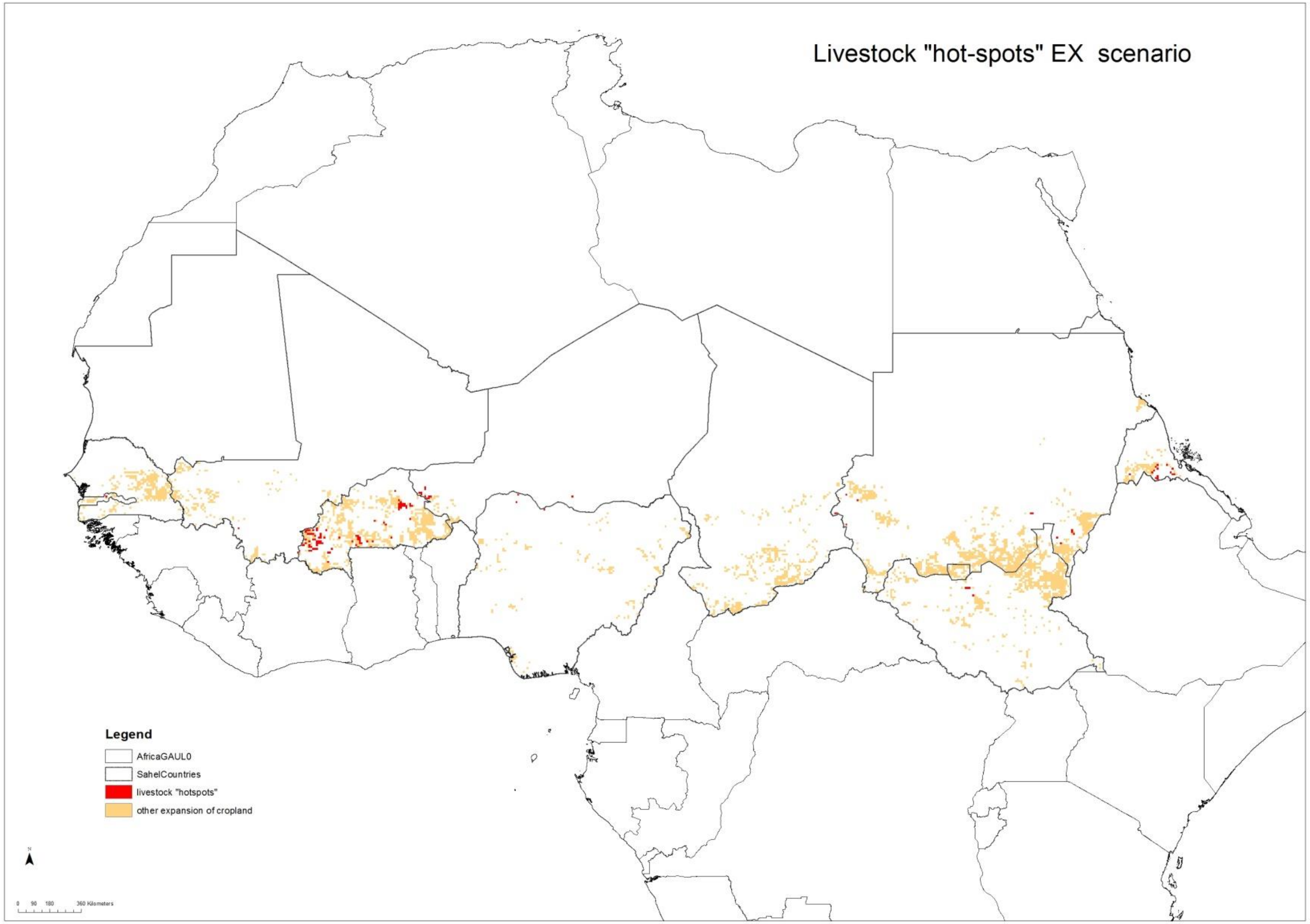

Figure 37 Map of livestock "hot spots" – EX scenario
Source: Own elaboration

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List of abbreviations and definitions

Abbreviation	Description
AEZ	Agro Ecological Zone
AfDB or BAD in French	African Development Bank
BU	Business as Usual scenario
C	Carbon
CC	Climate change
CCAFS	The CGIAR Research Program on Climate Change, Agriculture and Food Security
CGIAR	Consultative Group for International Agricultural Research
CIESIN	Center for International Earth Science Information Network
CILSS	Comité permanent Inter-Etats de Lutte contre la Sécheresse dans le Sahel
CIRAD	Centre de coopération internationale en recherche agronomique pour le développement
CSA	Climate Smart Agriculture
CSI-CGIAR	Consortium for Spatial Information of the CGIAR
ECOWAS or CEDEAO (*French*)	Economic Community of West African States
EBA	Ecosystem Based Adaptation
EF	Ecological Footprint
EX	Extension scenario
FAO	Food and Agriculture Organization of the United Stations
GCM	Global Circulation Model
GLASOD	Global assessment of soil degradation
HANPP	Human appropriation of Net Primary Production
IFPRI	International Food Policy Research Institute
IGBP	International Geosphere-Biosphere Programme
II	Input Intensification scenario

INRA	Institut national de la recherche agronomique
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
IPM	Integrated Pest Management
IPTS	Institute for Prospective Technologies Studies, JRC
IWMI	International Water Management Institute
JRC	Joint Research Centre of the European Commission
LTA	Long Term Average
LULC	Land use – Land cover
LUT	Land Utilisation Types
MII	Moderate Input Intensification
MODIS	Moderate Resolution Imaging Spectroradiometer
NPP	Net Primary Production
OECD	Organisation for Economic Co-operation and Development
SRES	Special Report on Emissions Scenarios
SSA	South Saharan Africa
TS	Technical Specifications
UN DESA	United Nations Department of Economic and Social Affairs
WWF	World Wildlife Fund

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doi:10.2760/500533

ISBN 978-92-79-74274-3