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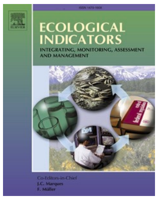

Towards assessing the resource criticality of agricultural livelihood systems

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ABSTRACT

Despite the many advantages of sustainable intensification (SI), the level of adoption of SI practices in African smallholding farms is still very low, highlighting the need for adequate methods for monitoring farm sustainability. Research on SI and related poverty alleviation strategies focus either on the "problems" or on the "solutions" for agricultural livelihood systems (ALS) with separate sets of indicators developed accordingly. Bridging the two approaches, we propose an indicator set to assess the criticality of a resource to ALSs in order to support smallholders, decision-makers, and practitioners in the process of SI. The set indicates what problems an ALS faces in the form of resource supply risks and the ALS's ability to successfully cope with such problems, i.e., how resilient it is to these supply risks. We apply the ALS criticality approach (ALSCA) to macronutrients in three different ALS types in the village cluster of Pontieba, Ioba Province, Burkina Faso. Two criticality indicators are highlighted. First, the three ALS types are not facing equal nitrogen supply risks, when the latter is informed by depletion time. The depletion time indicates the time until which a resource stock is depleted at the current mining rate. The average depletion time of soil nitrogen stocks ranges from some 10 to 165 years. Second, the reliance on own resources is an indicator measuring resilience to supply restriction. In Pontieba, regardless of macronutrient, reliance on own nutrients never surpasses 50% when ALS averages are considered. The study showed that the ALSCA can contribute to the implementation of SI practices through support at four levels: 1) providing a holistic view on the ALS to avoid problem-shifting and enable prioritization, 2) providing options to reduce resource criticality, 3) mutual learning between ALSCA practitioners and smallholder farmers through knowledge integration, and 4) facilitating policy coherence from local to national levels thanks to the ALSCA's applicability on different scales.

1. Introduction

1.1. *Sustainable intensification and African smallholding farms*

Sustainable intensification (SI) consists in intensifying agricultural production while preserving the environment (Smith et al., 2017). Sustainable intensification, for instance through integrated conservation agriculture, allows preserving land resources, a major advantage in the context of ever-growing land use conflicts (Mutabazi et al., 2014). Not to mention that increasing land use for crop and livestock production comes with losses of biodiversity (Matson et al., 1997; United Nations, 2009) and greenhouse gas (GHG) emissions (Stern, 2007). SI's core tenet is that intensification should not take place at the cost of environmental quality (Garnett et al., 2013). SI views the long-term preservation of soil and waterbody qualities as prerequisite for sustained agricultural production (Pretty & Bharucha, 2014). SI practices include a more efficient use of inputs such as mineral fertilizers to minimize upstream energy consumption and downstream pollution of water bodies through eutrophication (Cassman, 1999). Besides increasing yields while reducing pressure on the environment through SI, Garnett et al. (2013) stress the need to consider other policy goals in food systems and mention five related areas: biodiversity and land use, animal welfare, human nutrition (i.e., the need for a diverse diet), rural economies, and sustainable development.

Despite the advantages of SI practices provided the adoption of a broad perspective, the level of its adoption is still low in smallholding

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farms of sub-Saharan Africa (Guo et al., 2020). African smallholder farms produce most of the food consumed on this continent (HLPE, 2013; IFAD & UNEP, 2013). In Africa in the last 50 years, agricultural production stagnated in stark contrast to other continents, though the population on the continent more than doubled (Pretty et al., 2011). Sub-Saharan Africa suffers from important yield gaps, more than any other world region, as surveyed by Mueller et al. (2012). For instance, Tittonell and Giller (2013) noted a yield gap in Cassava of 12.2 t/ha in the East Africa Highlands. Pretty et al. (2011) reviewed 40 SI projects and programs developed during the 1990s-2000s in sub-Saharan Africa, ranging from conservation agriculture to agroforestry to integrated pest management. Results were promising with crop yields increasing by more than twofold in average. Yet, a wide-scale implementation is lacking (Guo et al., 2020; Pretty et al., 2011; Vanlauwe et al., 2014). Given low external inputs in fertilizers, African smallholder farming largely continues to rely on the mining of soil nutrients, and prolonged nutrient mining led to soil degradation and low yields (Craswell & Vlek, 2013; Drechsel et al., 2001a, 2001b).

1.2. The need to integrate problem- and solution-oriented SI research

Niehof and Price (2001) coined the term of livelihood system. It consists of processes interacting with each other or with their environment through the exchange of flows of resources (materials, energy, and money) to sustain a livelihood. An agricultural livelihood system (ALS) is a livelihood system mainly based on agricultural activities such as crop and livestock production. ALS processes are crop production, livestock production, aquaculture, forestry, organic fertilizer production (with or without energy recovery), stocks, household consumption, and agricultural trades (Van den Bosch et al., 1998). The livelihood consists mainly of agricultural products and income from selling these products. ALSs can be analysed on different scales, starting from the farm all the way to the world food production system. Other scales such as villages and landscapes are of interest as the latter include mineral fertilizer production facilities and water bodies necessary for agricultural production (Tittonell, 2014).

Problem-oriented research has focused on the sustainable supply of nutrients to crop and livestock production, as shown by the examples below. This research focus relies on econometric approaches linking variables with regression analysis and other statistical approaches. For instance, the combined application of mineral and organic fertilizers can potentially lead to lower or higher yields than the application of the one or the other in isolation (Chivenge et al., 2011; Pincus et al., 2016). Nutrient losses in composting are very much linked to farmer practices, e.g., with respect to manure storage (Tittonell et al., 2010). Indeed, prolonged manure storage periods can lead to the loss of ca. 70% of N, P, and K contained in manure. The need for knowledge in composting is an important problem in Sub-Saharan Africa (Mustafa-Msukwa et al., 2011). The examples presented here all relate to macronutrient problems, for which researchers rely on indicators such as yields or soil balances to suggest recommendations.

Solution-oriented indicators provide entry points to increase the resilience of ALSs against stress and shocks such as climate change. The emphasis here lies on ways and solutions to increase the socio-ecological resilience of ALSs, while very much needed intensification is carried out (Darnhofer et al., 2010a, 2010b; Folke et al., 2002). A solution-based approach to SI involves the consideration of socio-ecological factors determining the resilience of ALSs, such as indicators of natural, physical, human, social, and financial livelihood assets in the Sustainable Livelihoods Framework (SLF) (DFID, 1999). In recently extended theoretical frameworks, highlighted indicators are social network structure contributing to self-organization and financial capacity as well as functional and response diversity contributing to buffer capacity (Cabell & Oelofse, 2012; Ifejika Speranza et al., 2014). Both self-organization and buffer capacity in addition to learning capacity seem to be recurring indicator categories corresponding to capacities which enhance the resilience of a system to stress and shocks. However, little is said on the resilience of the ALS to specific shocks or stresses, such as the restriction in the supply of macronutrients mentioned above, or ways to increase this resilience. Moreover, indicators are evaluated on rather simplistic Likert scales.

We seek to integrate problem- and solution-oriented research on ALSs to develop an indicator set capable of supporting ALSs in the process of SI (Singh et al., 2012). We provide the dimensions, components, and candidate indicators of the indicator set and present the results for some candidate indicators in the case of a smallholder farming community in southwestern Burkina Faso. Following the Introduction (Section 1), Section 2 presents the approach for developing the indicator set with a focus on two candidate indicators. Section 3 shows the preliminary results of its application as case study. Section 4 provides a discussion of the benefits and limitations of this approach integrating problem-oriented research and solution-oriented indicators and an outlook of its further development and implications for practice.

2. The agricultural livelihood system criticality approach

2.1. The approach in a nutshell

The Agricultural Livelihood System Criticality Approach (ALSCA) provides indicators measuring ALS criticality to specific resources. The ALSCA aims at helping farmers, practitioners, and other relevant decision-makers identify criticality hot spots and ways to tackle these hot spots. The ALS is the unit of investigation. Fig. 1 details the characteristics of an ALS at the farm level using the software STAN (http://stan2web.net/). Multiple flows exist between the main five processes of an ALS: primary production units for crop production, secondary production units for livestock production, household, stock (e.g., crops), and redistribution units (e.g., composting). The ALS exchanges materials with its environment beyond the system boundaries. In each process, materials can be accumulated as stocks.

Only the understanding of the system as a whole and in its context allows for deriving recommendations that hinder problem-shifting (Venkatesh & Brattebo, 2009). A systemic approach therefore allows setting priorities with respect to action on processes and flows in such a way that solving one issue does not create a new one. The ALSCA can be used for assessing the criticality of ALSs, starting from the farm level in the context of SI. The approach allows assessing how critical a resource is to a farm, a village, a landscape, and the globe as a whole. The approach encompasses three major steps: i) defining the ALS types; ii) conducting a material flow analysis of the ALS types; and iii) performing the criticality assessment. The ALSCA is adapted from the methodology of metal criticality determination or Yale criticality methodology that links problems to solutions in the field of metal usage in industry (Graedel et al., 2012). Three dimensions make up criticality in that methodology: supply risk, vulnerability to supply restriction, and environmental implications. The next section describes the three steps in detail.

2.2. The three ALSCA steps

2.2.1. Definition of types of agricultural livelihood systems

This step allows identifying the ALS typology. Based on the observed structural and functional heterogeneities of ALSs (Le, 2005; Thiombiano & Le, 2015; Tittonell et al., 2005), agricultural research has acknowledged the need to tailor SI policies to different ALS types (Le, 2005). If a case study includes a rather large sample of farms, which is probably the most frequent instance, the definition of an ALS typology is a prerequisite for the material flow analysis. The latter and the ensuing criticality assessment then distinguish the individual ALS types.

2.2.2. Material flow analysis (MFA)

MFA is a method used to compile and visualize the stocks and flows

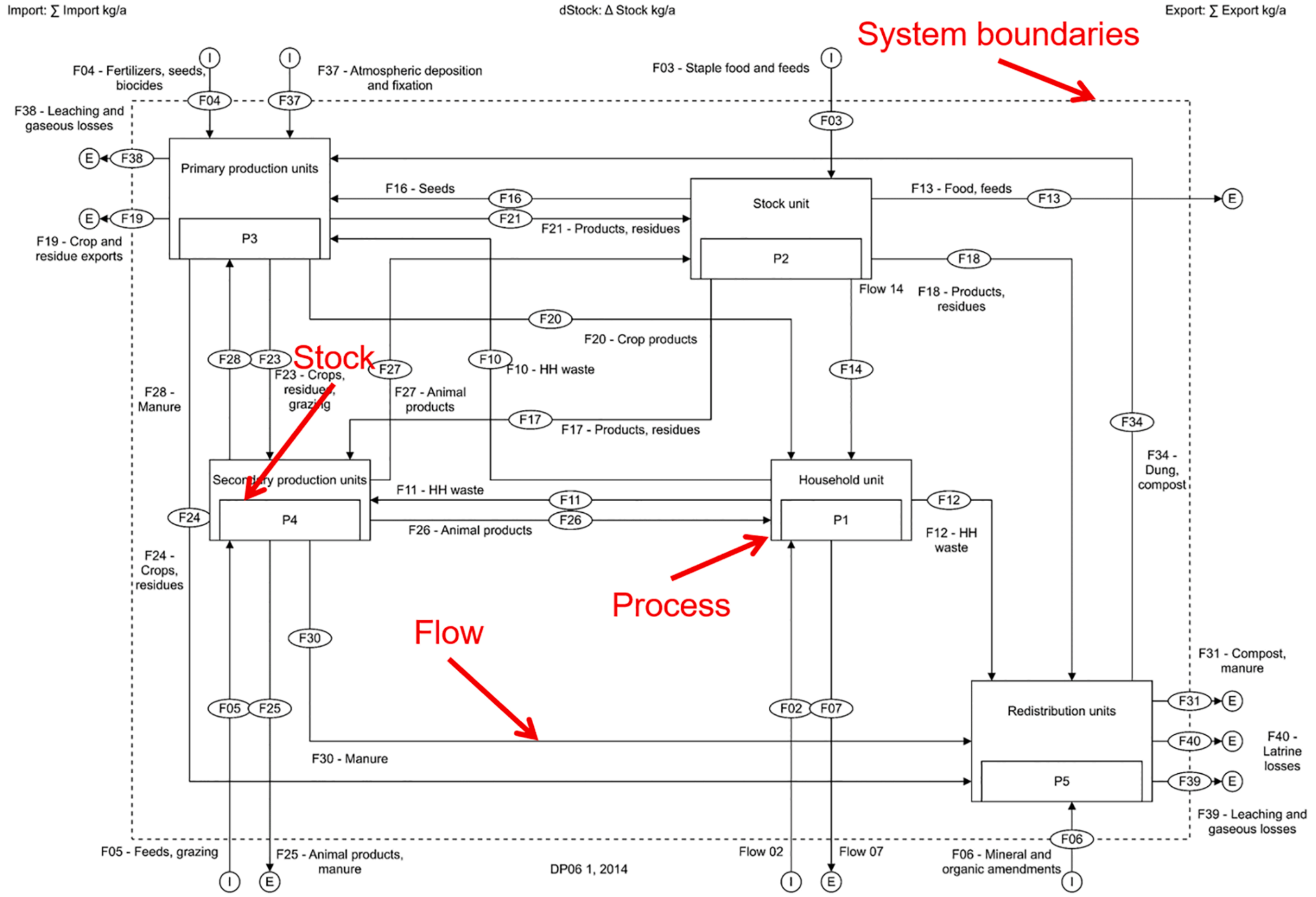

Fig. 1. Agricultural livelihood system and its characteristics. Adapted from Meylan et al. (2017)

of any material in any environmental, human, or human-environment system for a given time and geographical entity (Alfonso Piña & Pardo Martínez, 2014; Brunner & Rechberger, 2004). MFA provides an understanding of what and how much material is mobilized (Leray et al., 2016). The following methodological steps are applied sequentially in an MFA of ALS at the farm level:

1. Definition of a qualitative flowchart: Fig. 1 gives the qualitative flowchart of an ALS at farm level as defined by Van den Bosch et al. (1998). The processes of smallholder farms are:
   - Primary production units (PPU, i.e., crops)
   - Secondary production units (SPU, i.e., livestock)
   - Redistribution units (RU, e.g., compost heap or pit, stable, dung pool, and latrines)
   - Household unit (HH)
   - Stock unit (i.e., food and energy reserves, and money savings)
2. Data collection to populate the stocks and flows of the qualitative flowchart.
3. Application of the mass balance principle to calculate flows or net additions to stock that cannot be measured directly or modeled otherwise. For instance, on Fig. 1, the following equation holds for the process “Secondary production units” (SPUs, Process P4):

$$F05 + F17 + F23 = F25 + F26 + F27 + F28 + F30 + NAS_{SPU} \tag{1}$$

where $F05$ is the import of feeds and grazing into SPUs, $F17$ is the flow of products and residues from the stock unit into SPUs, $F23$ is the flow of crops, residues, and grazing into SPUs, $F25$ is the export of animal products and manure from SPUs, $F26$ is the flow of animal products from SPUs into the HH, $F27$ is the flow of animal products from SPUs into the stock unit, $F28$ is manure from SPUs into PPUs, $F30$ is manure from SPUs into RUs, and NAS_{SPU} is the net addition to stock in SPUs (in the form of livestock).

4. Interpretation to highlight the important flows and indicate the most important sources and sinks of materials, be it stocks of process within the system or imports and exports to and from the system. Indicators allow comparing the systems in terms of scales of resource flows, e.g., the rate of recycling by composting:

$$R_{Recycling} = \frac{F31 + F34}{F12 + F18 + F24 + F30} \tag{2}$$

where $F31$ is compost and manure exported from RUs, $F34$ is compost and manure from RUs into PPUs, $F12$ is household waste into RUs, $F18$ is the flow of products and residues from the stock unit into RUs, $F24$ is the flow of crops and residues from PPUs into RUs, and $F30$ is manure from SPUs into RUs.

2.2.3. *Criticality assessment*

The ALSCA yields a composite index made up of three dimensions: supply risk, resilience to supply restriction, and environmental implications. Each dimension is evaluated based on an aggregated score of components. For instance, the higher the supply risk a farm is facing, the higher is its criticality index. Component scores are in turn a weighted average of candidate indicators. For instance, the more the soil nutrients are depleted, the higher the supply risk. We adapt the existing Yale metal criticality methodology (Graedel et al., 2012) to reflect characteristics of smallholder farms (Meylan et al., 2017). Smallholder farms, closely embedded within ecosystems, are indeed very different from industrial corporations using metals.

The first adaption concerns the criticality dimension of supply risk. In contrast to countries and corporations supplied with metals from mines spread all over the world, we consider the soil as the mine in an ALS. Farmers can recharge the soil mine by applying mineral and organic fertilizers. In this dimension, we are therefore not interested in the various risks associated with the mineral extraction of phosphorus and potassium or with ammonia synthesis (Erisman et al., 2008). The depletion time (Nassar et al., 2012, 2015; Nuss et al., 2014) of the soil reflects the pedological supply risk. The path between the soil viewed as a nutrient mine and the edible component of the crop is paved with further risks (Balboa et al., 2018). First, not all soil nutrients are present in a form available to the plant. Second, nutrient losses may arise from poor management by farmers. Third, macronutrient uptake takes place at the soil-root interface and shows different efficiencies. The associated risk depends on the soil type, the weather condition (e.g., wetness), and the crop. Finally, crops themselves have different conversion efficiencies.

The second adaptation concerns the criticality dimension “vulnerability to supply restriction”. We replace the criticality dimension “vulnerability to supply restriction” with “resilience to supply restriction” to take advantage of the existing solution-oriented research (see Section 1.2). In the original Yale methodology (Graedel et al., 2012), three components have been proposed for vulnerability to supply restriction: (i) *importance*, denoting how important a metal is to a corporation, (ii) *substitutability*, which presupposes a substitute to a metal in a specific function (e.g., a substitute of zinc in coating), and (iii) *the ability of a corporation to innovate* in order to overcome a supply restriction. Instead, the components of resilience to supply restriction are (i) *buffer capacity*, (ii) *self-organization*, and (iii) *capacity for training* (Ifejika Speranza et al., 2014). There is no one-to-one connection between components of the original and adapted criticality methodologies. The *ability to innovate* is explicitly mentioned in *buffer capacity,* indicated by livelihood capitals such as human capital, and in *self-organization*, as network interactions can result in innovation (Ifejika Speranza et al., 2014). Closely linked to the *ability to innovate* is the *capacity for learning* (Cabell and Oelofse, 2012; Ifejika Speranza et al., 2014), as this capacity is a perquisite for innovation (Çömlek et al., 2012). *Substitutability* has no equivalent in the adapted methodology, as soil nutrients are not substitutable in plant growth, in contrast to metals in many cases. Also, nutrients fulfill other functions than supporting crop growth such as alleviating the toxic effects of heavy metals (Sarwar et al., 2010). Finally, *importance* is covered by *buffer capacity* through the diversity of income sources.

In the third dimension, environmental implications, we introduce two components to reflect local and global environmental impacts of the

Table 1
Components and candidate indicators of ALSCA in the case of macronutrients and smallholder farms.

Criticality dimension	Component	Candidate indicators		
Supply risks	Pedological	- Depletion time of soil stock	*Soil forming rate:* -Soil type (associated bedrock type) -Ambient soil depth -Landscape/catenary position	
	Technological	- Tillage practice - Fertilizer use practice (type, form, placement method, scheduling) - Intercropping practices		
	Soil-crop interface	- Uptake efficiency (crops taking up nutrients applied to soil by crops)		
	Agro-biogenetical	- Conversion efficiency (up-taken nutrients converted to food crop products, e.g., grains, fruits, tubers, vegetables)		
Resilience to supply restriction	Buffer capacity	*Human capital:*	*Subsidiary interactions:*	*Diversification:*
		- Labor availability	-Subsidiary connectivity among farm components	-Diversity of farm production components
		- Knowledge on baseline of own farming system	-Reliance on own resources (e.g., no mineral fertilizers, pesticides and subsidies)	-Diversity of income sources
		- Management skills/experiences		- Diversity of supplier sources and output markets- Human capacity for internal innovation - Diet diversity
	Self-organization	*Ecologically self-regulated:* - Closer nutrient loops	*Socially self-organized:* -Ability and experience to organize into cooperation networks and institutions in response to new supply shortages	
	Capacity for reflective, effective learning	- Access to learning network (training by extension services, agricultural universities/ research centers, farmers association/schools) - Existence of implementation of learned technologies and/or management methods - Existence and performance of own monitoring and evaluation routines		
	Global component	*Cradle-to-gate environmental impacts of mineral fertilizer production (list is not exhaustive):* - Greenhouse gas emissions		
	Environmental implications	-Water use		
	Local component	*Impacts of mineral and organic fertilizer application on the farm’s natural environment (list is not exhaustive):* - Soil salinization - Ecotoxicity		

macronutrients. The global component consists in cradle-to-gate environmental impacts of mineral fertilizer production. The local component is concretized as the impacts of mineral and organic fertilizer application on the farm's natural environment like eutrophication and soil salinization. The rationale for this third criticality dimension is the following. Relying on mineral fertilizers can be critical to smallholders merely because of the environmental impacts their production causes. Likewise, downstream environmental impacts of fertilizer use are potentially critical to smallholders. While readily-available databases inform the global component (ecoinvent Centre, 2010), assessing local environmental impacts requires detailed case knowledge to take into account local soil properties and water body sensitivities.

Table 1 provides the components and respective candidate indicators for macronutrient criticality determination applied to smallholder farms. As explained above, in the adapted methodology, vulnerability to supply restriction becomes resilience to supply restriction. In supply risk, the depletion time of the soil stock is calculated by dividing the soil macronutrient stock by the macronutrient balance, the latter informed by the MFA. The component and indicators of resilience to supply restriction are informed by the literature on resilience indicators presented above. Still in this component, the reliance on own resources corresponds to the ratio of organic fertilizers used to the sum of organic fertilizers used, soil macronutrients mined, and mineral fertilizers used, all of which are informed by the MFA. Furthermore, various metrics can be of interest in social networks, yet one must note that such networks exist only for a specific process, e.g., cooperation for access to a resource or collaboration in a policy process (Carrington et al., 2005; Ingold, 2011).

After proposing components and candidate indicators of a new nutrient criticality methodology, indicators must be operationalized and indicator values be converted to a scale from 0 to 100% to allow for aggregation to single scores of supply risk, resilience to supply restriction, and environmental implications. As already hinted above and in contrast to Ifejika Speranza et al. (2014), wherever possible, we use an empirical approach to measure indicators instead of systematically applying a Likert scale. Each indicator value is then converted to a value between 0 and 100%, as in the original metal criticality methodology, with high values denoting a high supply risk, high resilience, or high environmental implications. The ALSCA practitioner is free to give equal or different weights within components and dimensions with the support of existing tools (Becker et al., 2017). The current practice in metal criticality determination is to give equal weights (Graedel et al., 2015; Harper et al., 2014; Ioannidou et al., 2017; Nassar et al., 2012; Sonderegger et al., 2015).

3. Case study

3.1. Definition of ALS types

Thiombiano & Le (2015) identified three ALS types in the village cluster of Pontieba, Ioba Province, Burkina Faso:

- Livelihood type 1: Poor, landless, and subsistence-based farms,
- Livelihood type 2: Medium-income, high dependency ratio (i.e., number of dependents in the household divided by the number of working-age individuals), cotton- and livestock-turned, and
- Livelihood type 3: Better-off, land- and labor-rich, cotton- and livestock-turned.

More details on the ALS typology are provided in the previously cited work.

3.2. Material flow analysis

All flows were informed by models or primary data collected in the framework of a nutrient monitoring (NUTMON) survey (Van den Bosch et al., 1998) conducted for 15 households, five from each ALS, from March 2013 to February 2014 (Thiombiano, 2015). Fig. 2 shows the MFA of N of a farm identified as DP06 belonging to ALS type 1 (as example). Table 2 gives an overview of the MFA results for ALS type 1. More details on the MFA results are provided in Meylan et al. (2017). The Supplementary Material includes all MFA results, including those for farms belonging to ALS types 2 and 3. All 15 MFAs are provided as STAN files. The interested reader can freely download the STAN software at http://stan2web.net/. Once STAN is installed, the reader can open the STAN file of a specific farm and view its nitrogen, phosphorus, and potassium flows by selecting the appropriate layer. The reader can further implement scenarios in STAN files, for instance the recycling of all organic nutrients and derive new values of indicators, e.g., those developed for the ALSCA.

Results of status quo MFAs exhibit both differences and similarities between the three ALS types. Different processes dominate the farms in terms of material flows. The ALSs present different scales of flows, with maximum flows ranging from 48 to 145 kg N/ha/yr in the case of nitrogen. Similarities include low recycling rates, thereby making redistribution units an important sink. Also, phosphorus from mineral fertilizers accumulates almost entirely in soils.

3.3. Criticality assessment

Fig. 3 presents the operationalization results of two ALSCA candidate indicators: (a) depletion time of soil stock in the dimension of supply risk and (b) reliance on own resources in the dimension of resilience to supply restriction. The indicators were initially developed in Meylan et al. (2017). Averages, maxima, and minima were computed for the three ALS types of Pontieba. Regarding depletion time (a), the nutrient soil stocks were provided by Thiombiano (2015), while Meylan et al. (2017) computed the soil nutrient balances (also known as net additions to stock, NAS) using MFA. Some values do not exist due to positive soil nutrient balances. Such farms therefore present a low supply risk for that indicator. The nitrogen supply risk differs greatly between the three ALS types, as average depletion time ranges from some 10 to 165 years. ALS types 1 and 3 have short nitrogen (10 and 40 years, respectively) and potassium (55 and 35 years, respectively) depletion times compared to ALS type 2 (165 years for N, 110 years for K). Reliance on own resources (b) was computed using the MFA results (Meylan et al., 2017). No average surpasses 50% in terms of reliance on own resources. In the case of nitrogen and potassium, no maximum surpasses 50%. Resilience to supply restriction is therefore low, when this indicator is considered. The indicator depletion time requires further conversion to a 0–100% scale of supply risk. In contrast, a reliance on own resources of 25% as in ALS type 1 for nitrogen corresponds to a score of 25% in resilience to supply restriction for that specific indicator.

4. Discussion and outlook

4.1. Contribution of the ALSCA to sustainable intensification

We believe the agricultural livelihood system criticality approach (ALSCA) can contribute to orienting ALSs to a trajectory of sustainable intensification through *actions* at four levels. It not only aims at highlighting problems on the supply side of macronutrients, but also actions that farmers can implement in order to increase their resilience to supply restriction. For instance, a complete ALSCA indicator set will highlight to what extent strengthening social networks relevant to nitrogen supply will reduce nitrogen criticality.

The ALSCA starts with a material-biophysical characterization of the problems a group of ALSs (e.g., village cluster) faces. By not focusing on a specific farm process (e.g., soil) or element (e.g., nitrogen) but on the system as a whole, farmers can identify the most relevant sinks or macronutrients, so that the ensuing criticality assessment is as effective as possible and no resource problems are overlooked. While MFA provides this holistic understanding, the previous clustering of farms into

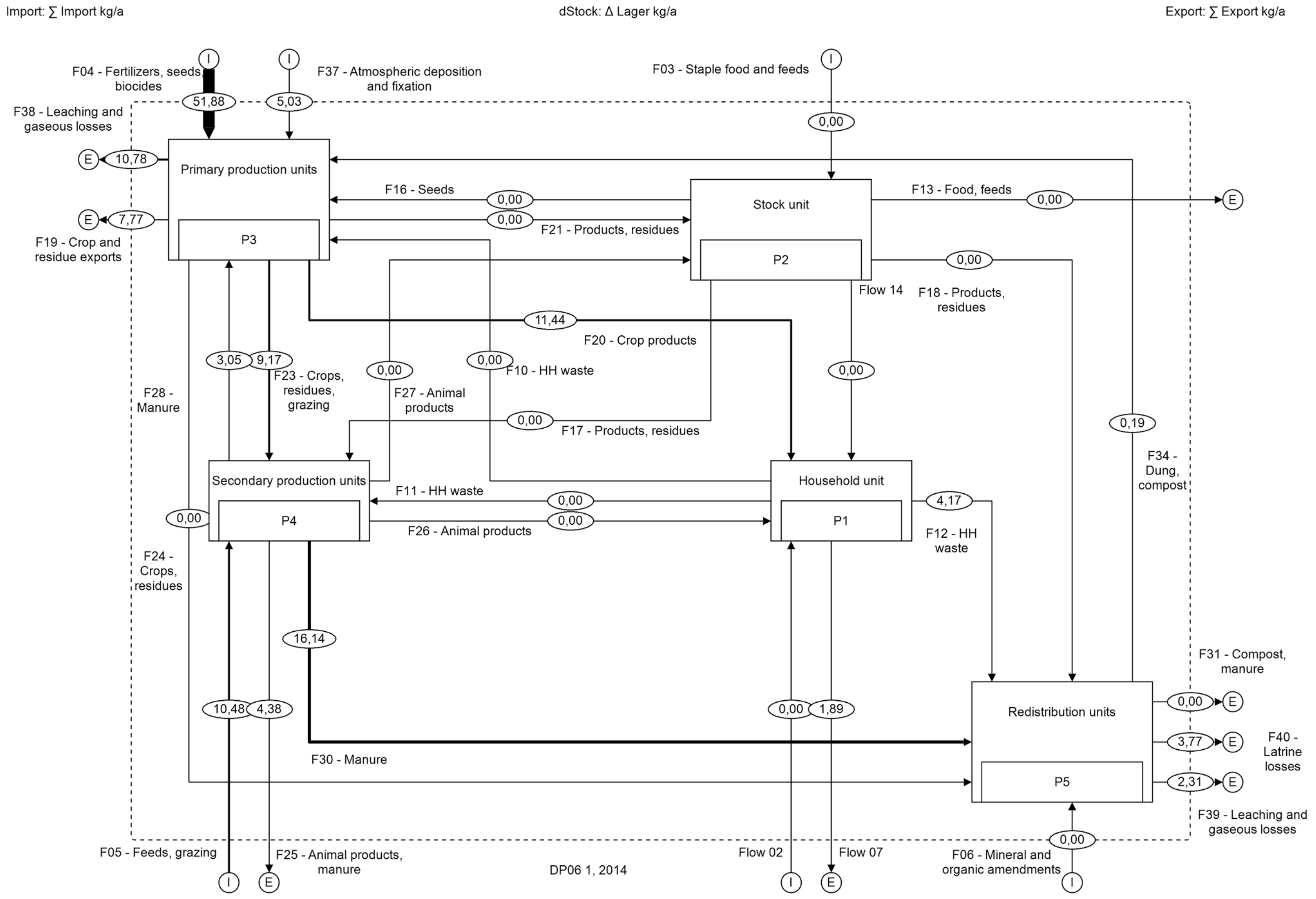

Fig. 2. Material flow analysis (MFA) of nitrogen (kg/ha/yr) of agricultural livelihood system (ALS) 1 (farm DP06). Source: Meylan et al. (2017).

Table 2
Overview of MFA results for ALS type 1.

Nutrient	Largest flows	Soil balances	Main sources	Main sinks	Highest recycling rate
Nitrogen	Maximum of 52 kg N/ha/yr (mineral fertilizers) - Mineral fertilizers - Crops and residues leaving the system (as marketable goods or gifts) - Nutrients leached or lost otherwise to the environment	From −16 to 21 kg N/ha/yr	- Mineral fertilizers - Soil nutrients	- Redistribution units - Crops and residues leaving the system - Nutrients leached and other losses to the environment from primary production units	2%
Phosphorus	Maximum of 43 kg P/ha/yr (mineral fertilizers) - Mineral fertilizers - Household waste to redistribution units - Manure to redistribution units - Feeds, grazing imported into secondary production units	From −0.9 to 32 kg P/ha/yr	- Mineral fertilizers - Soil nutrients - Deposition - Feeds, grazing into secondary production units	- Animal products leaving secondary production units - Crops and residues leaving the system - Latrine losses	1%
Potassium	Maximum of 26 kg K/ha/yr - Crops, residues, grazing from primary to secondary production units or leaving the system - Manure from secondary production to redistribution units	From −31 to −6.5 kg K/ha/yr	- Mineral fertilizers - Soil nutrients	- Redistribution units - Crops and residues leaving the system - Nutrients leached and other losses to the environment from primary production units	2%

ALS types allows investigating the criticality of homogenous systems and formulating tailor-made recommendations. The case study of the village cluster of Pontieba demonstrated that the ALS types show important differences both in terms of functions and macronutrient flows.

The ALSCA, through its dimension of resilience to supply restriction, seeks to provide multiple ways (Loorbach & Rotmans, 2010) to tackle a specific resource restriction – a portfolio of actions by different agents (rather than only farmers). The latter act and affect the sustainability and resilience of ALSs at different scales that include nodes beyond the

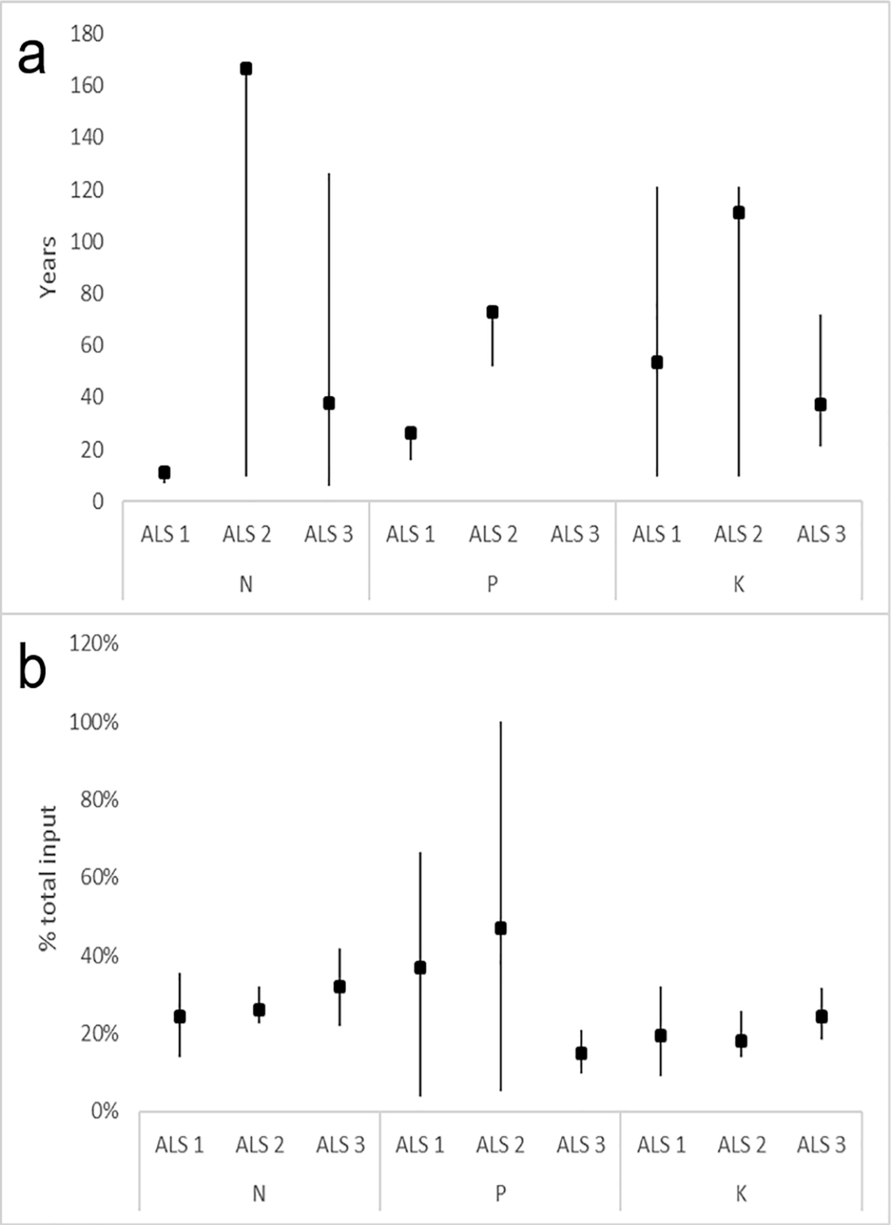

Fig. 3. Values of soil stock depletion time (a) and reliance on own resources (b) for N, P, K in ALSs of Pontieba. Averages are represented as dots, maxima and minima as high-low vertical bars. Adapted from Meylan et al. (2017)

smallholder farm boundaries (Tendall & Gaillard, 2015; Tendall et al., 2015). Within each component and candidate indicators, farmers and/or relevant decision-makers can take corresponding action, monitor progress, and continue or not with a particular action depending on its efficacy. Actions taken with respect to different indicators can potentially reinforce each other (Loorbach & Rotmans, 2010; Rotmans & Loorbach, 2009). Concretely, introducing brokers into fragmented networks of ALSs to pass on innovations or increasing recycling of macronutrients through composting are actions to decrease criticality regarding social network structure and reliance on own nutrients, respectively. The farmers of Pontieba clearly expressed needs for continuous training in the field of composting.

The problem-oriented research described in Section 1.2 relies often on farmer questionnaires, where knowledge flows in one direction (Weißhuhn et al., 2017). The ALSCA, with the knowledge integration it presupposes, implies an exchange of more diverse forms of knowledge between farmers and ALSCA practitioners and leads to mutual learning (Walter et al., 2008; Wiek & Walter, 2009). For instance, investigating social networks related to the exchange of nutrients between farms requires intensive interaction with farmers. Such interactions can result in raising awareness of farmers about network benefits (Manson et al., 2016). We conducted workshops with farmers and other stakeholders in the framework of the case study. These workshops revealed the importance of networks of farmers, community leaders, government agencies, market actors, credit institutions, etc. in delivering (or not) crop and livestock productivity.

The need to increase policy coherence of developed countries to enhance food security in emerging and developing economies has long been acknowledged (Brooks, 2014; Carbone, 2008). There is also a need for policy coherence in the water-agriculture nexus (OECD, 2012). As the ALSCA can be applied to any ALS scale, it could contribute to increased policy coherence across scales in reducing criticality of soil macronutrients, water, and other resources by providing a common language (MacDonald et al., 2019). Advancing crop and livestock productivity in Pontieba certainly requires developing consistent national, regional, and local agricultural policies. The ALSCA can provide the template for such an endeavor.

4.2. Limitations and recommendations

A first limitation is inherent to the structure of the indicator set itself. Resilience is increased through high diversity in all three components of resilience to supply restriction (Ifejika Speranza et al., 2014). The ALSCA cannot assess the risk of a cross-cutting component like diversity. In addition, while the role of diversity in increasing resilience is well understood (Cabell & Oelofse, 2012), developing indicators for it seems to be a more intricate task. The fact that diversity can be further split into response and functional diversities (Finney & Kaye, 2017; Snowdon et al., 2019) certainly does not make this task easier.

The second limitation comes from the use of only MFA as operational method to measure the indicators. In Table 1, many candidate indicators can only be measured through the use of social research methods (e.g., indicators for social self-organization and impacts on social fairness), and quantitative economic assessment (e.g., indicators of diversity of income sources). This calls for a mixed-methods approach (Higgins & Caretta, 2019; Mutenje et al., 2019) that use different methods in a complementary way to evaluate comprehensively all criticality dimensions of ALS.

The other limitation arises from the little experience we have in applying the ALSCA in case studies. While we are confident that the components are well grounded in theory, and can be further refined or adapted as (resilience) theory evolves (Bollettino et al., 2017), our practical experience with indicators is limited to depletion time and reliance on own resources within the domain of smallholder farms and households. A complete case study is needed to test existing candidate indicators with respect to feasibility, develop or adopt further indicators, and identify meaningful mathematical functions to convert measurements, e.g., social network structure metrics, onto a 0–100% scale of criticality.

4.3. Outlook

Further application of the ALSCA is needed not only to test indicators, but also to investigate its adequacy in other contexts, for instance in other regions of Sub-Saharan Africa, and at other scales than farms such as villages and landscapes. In the Pontieba case study (Thiombiano, 2015), we captured little of the variation usually observed across the agrarian communities and time. Sustainability and resilience studies have a long-term perspective and are performed over interconnected, often mismatched, spatial scales (Cumming et al., 2013). We thus need to apply, refine, and validate the ALSCA in other agricultural communities beyond Burkina Faso and over time. The SMART criteria (Prather, 2005; Robinson et al., 2009) would be an appropriate guide for this investigation in a meta-analysis of ALSCA case studies. SMART is an acronym standing for sound, measurable, accepted, realistic, time bound. The potential improvements justify the efforts for conducting such ALSCA case studies. Also, much of the data needed in the ALSCA is already collected in the framework of nutrient monitoring studies (Van den Bosch et al., 1998) in the case of the MFA or readily available in the case of global environmental impacts of mineral fertilizers. Ultimately, it will be interesting to see what ways to increase resilience look like across different regions, with the ALSCA playing the role of trigger for a particular solution. One could indeed expect that strengthening social networks in Burkina Faso to increase resilience to nitrogen supply restriction looks somewhat different from strengthening networks in India (Rockenbauch & Sakdapolrak, 2017).

In Section 4.1, we showed that knowledge integration in the ALSCA goes beyond questionnaires to farmers and operational modelling like MFA. The appropriate application of the ALSCA would therefore entail a strong involvement of local policy-makers and researchers through their participation not only in designing and refining the ALSCA. They should also be able to promote mutual learning in ALSCA application. At a certain point, the question of streamlining the approach might pop up.

CRediT authorship contribution statement

Grégoire Meylan: Conceptualization, Methodology, Formal analysis, Data curation, Writing - original draft, Visualization, Project administration, Funding acquisition. **Boundia Alexandre Thiombiano:** Conceptualization, Data curation, Writing - review & editing, Visualization. **Quang Bao Le:** Conceptualization, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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