ARTICLE IN PRESS

Global Food Security xx (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Global Food Security

journal homepage: www.elsevier.com/locate/gfs

Measuring sustainable intensification in smallholder agroecosystems: A review

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ARTICLE INFO

Keywords:
Sustainability
Indicator
Metric
Agricultural development

ABSTRACT

Sustainable intensification (SI) is at the forefront of food security discussions as a means to meet the growing demand for agricultural production while conserving land and other resources. A broader definition of SI is emerging that takes into account the human condition, nutrition and social equity. Next steps require identification of indicators and associated metrics, to track progress, assess tradeoffs and identify synergies. Through a systematic, qualitative review of the literature we identified SI indicators, with a primary focus on African smallholder farming systems. We assessed indicators and metrics for which there is consensus, and those that remain contested. We conclude that, while numerous metrics for evaluating SI systems exist, many often-cited indicators lack strong sets of associated metrics.

1. Introduction

Food security is threatened by rising food demand, a degrading resource base and a changing climate, all at a time when nearly a billion people suffer from malnutrition and even more experience nutrient deficits (Godfray and Garnett, 2014). In order to ensure future food security and meet current needs, sustainable intensification (SI) has been put forward as a key approach. Godfray et al. (2010) define sustainable intensification as the process of "producing more food from the same area of land while reducing the environmental impacts". Many resource-limited smallholder farms have a great potential for increased productivity (Herrero et al., 2010; Pretty et al., 2011). Given that many smallholder farmers suffer from malnourishment and rely largely on their own agricultural production (Garrity et al., 2010), SI of these systems has the potential to increase human wellbeing while strengthening the foundations of future food security. Though there is widespread agreement on the need to increase productivity and sustainability in smallholder agroecosystems, SI is an evolving concept that has been the subject of debate. Initially SI was presented as a collaborative project between researchers and farmers to increase food production while paying attention to environmental, social and economic sustainability (Pretty, 1997). Since then, some authors have expressed concern that SI has come to be used in a productionist sense, with concerns for sustainability and equity taking second place (Loos et al., 2014; Tittonell, 2014). This has prompted the use of 'ecological intensification' as an alternative term suggesting a greater focus on ecological principles and environmental sustainability (Cassman, 1999; Petersen and Snapp, 2015). However, in the view of many, SI has a strong focus on ecological integrity, social sustainability and the human condition (The Montpelier Panel, 2013). Given this contention, it is necessary to define boundary conditions for what can be placed under the rubric of SI (Tittonell, 2014). These boundary conditions, in turn, are defined by the metrics that we use to measure and evaluate SI systems.

In recent years there have been many calls to define and elaborate metrics of SI in order to lend the concept greater clarity and bring increased coherence to the field of SI research (Struik et al., 2014; The Montpelier Panel, 2013). Our objective is to report on a literature review that considers the current state of thinking on SI indicators and concrete metrics used to assess them, highlighting areas of consensus and contestation. This is an important next step in efforts to develop context-appropriate metrics and improve understanding of SI in smallholder systems.

Abbreviations: SI, sustainable intensification

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http://dx.doi.org/10.1016/j.gfs.2016.11.002
Received 15 April 2016; Received in revised form 9 July 2016; Accepted 4 November 2016
Available online xxxx

2. Methodology and terminology

We searched the scientific literature using Web of Science and Google Scholar for references to SI and smallholder agriculture systems. Additionally, we searched for literature that employed related terms, namely, ecological intensification, climate-smart agriculture and eco-efficient agriculture. From these searches, we identified publications that focused on SI indicators and metrics appropriate to smallholder systems at the field, farm/household, and landscape or community scales. Papers that did not explicitly refer to SI or related terms, but that focused on both intensification and sustainability in smallholder systems were regarded as valuable and eligible for inclusion. Literature referenced in this review includes peer-reviewed journal articles, academic books and book chapters, academic conference proceedings, and public reports by well-known international agricultural research organizations. Agronomic studies of smallholder agriculture in Africa receive a strong emphasis in this review due to the authors' areas of expertise, and the focus of SI literature on agricultural development.

Two general classes of publications were identified: I) publications defining SI and presenting a range of SI indicators or described metrics appropriate to SI systems (46 publications), and II) publications that describe and evaluate SI efforts in the field (60 publications, see Table 1). We applied the following criteria for inclusion of publications in our review:

- The study must have been conducted in a smallholder system or define SI indicators relevant to this system. This includes on-farm research trials, but excludes trials performed on agricultural stations. The size criteria regarding what should be considered a smallholder system varied from one study to the next, as this criterion is dependent on bioregion and farm type.
- The study must have explicitly evaluated both productivity and at least one aspect of sustainability.
- The study must have employed and clearly described SI-relevant metrics. These metrics must go beyond simply crop yield or adoption of a technology.

Overall, we included 104 references describing and evaluating SI efforts in the field. These publications dealt with themes of productivity, economic, environmental and social sustainability, and human wellbeing in both crop and livestock systems. Table 1 presents a summary of the papers and the themes, related to the systems (crop, livestock, and integrated crop livestock) that they covered. Of all the publications we reviewed, only 22% originated from the same group of authors. To test if our literature review captured diverse views, we assessed if publications originated from the same author group: this was scored as a yes if they shared two authors in common (or shared a single author in the case of works with one or two authors). 82% of reviewed publications evaluating SI efforts in the field dealt with work in Africa, 8% dealt with work in Asia, and 10% dealt with work in the Americas.

Table 1
The sixty publications included in this review are summarized here by the domains of sustainability that they deal with, and the types of agricultural systems that they encompass. Values are numbers of publications cited in this review. Note that some publications dealt with multiple domains of sustainability and both crop and livestock (or integrated crop/livestock) systems.

Domain of SI	Crop systems	Livestock systems	Crop, Livestock or Integrated
Productivity	40	11	45
Economic sustainability	23	6	26
Human wellbeing	12	3	15
Environmental sustainability	36	9	39
Social sustainability	15	6	18
Total across domains	53	15	60

This paper assigns specific meanings to the terms "indicators" and "metrics." We use the term "indicator" to denote a quality or concept that is cited in the literature as an essential component of sustainable intensification. "Metric," on the other hand, refers to a specific property of a cropping system, farm system, household or community that can be directly measured. Indicators can have numerous metrics associated with them. For example, for the indicator biodiversity, a wide range of measurable properties are employed–the metrics. Among these are species richness, relative abundance of species, and functional diversity..

3. Widely used indicators and metrics of SI

We organized SI indictors identified in literature into five domains: productivity, economic sustainability, environmental sustainability, social sustainability and human wellbeing. Indicators within each of the domains are disaggregated by frequency of appearance in the scientific literature. While many SI indicators have quantifiable metrics, there are some exceptions (Tables 2–6). A key goal of this paper is to present SI metrics that can be broadly applied in different contexts. Indicators of sustainable intensification can be grouped into three main categories: indicators with limited application, indicators that communicate adequately, and indicators that can be applied broadly to evaluate system performance. In the following section we describe some of the most broadly applied indicators and the metrics associated with them. A complete list of indicators and their associated metrics is presented in Tables 2–6.

3.1. Indicators and metrics of productivity

3.1.1. Yield

Yield is by far the most common indicator used in the SI literature (Table 2). In cropping systems, yield refers to the production of crops per unit land area (Mg grain ha^{-1}). In livestock systems, yield is measured as the production of animal products (milk, meat or eggs) per livestock animal per day (Chigwa et al., 2015; Lusigi, 1995), or the production of milk per animal per lactation period (Descheemaeker et al., 2011). Livestock yield is also measured as the conversion efficiency of grain into meat, in kg meat kg^{-1} grain as feed (Herrero et al., 2010). Farmer-assessed range condition is a participatory approach to assessing yield applied only to livestock systems, which could be modified for use in integrated crop-livestock systems (Klintenberg et al., 2006).

One variant on crop yield that is highly relevant to the mixtures of species commonly grown on many smallholder farms is the land equivalent ratio (LER) (Altieri, 1999; Valet and Ozier-Lafontaine, 2014), used to measure the yield of intercrop systems relative to monocrops. An LER greater than 1 indicates that the intercrop is more productive than when the available land is devoted to sole cropping of the crops involved. This is currently only applied to cropping systems, but potential could be of value as an approach to consider for mixed livestock systems.

An associated SI productivity indicator is the yield gap, or the difference between the actual yield of the cropping system and the attainable yield (Mueller et al., 2011; Tittonell, 2013). The attainable yield is the yield that could be achieved under existing soil conditions, water availability, solar radiation and temperatures if all nutrient stresses and pest pressures were removed (Table 2). There are numerous methods for determining attainable yield. One commonly used approach involves simulating crop growth using crop growth models parameterized with local soil and historical climate data (Wani et al., 2003). As an alternative metric appropriate to resource-limited farms, Tittonell (2013) propose a locally attainable yield, based on the