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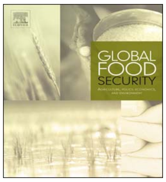

Measuring sustainable intensification in smallholder agroecosystems: A review

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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.

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*Abbreviations:*SI, sustainable intensification

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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

Table 2
SI indicators of productivity with their associated metrics, organized by scale. Indicators in normal font are cited by 3–7 sources, indicators in **bold** are cited by 8–14 sources, and indicators in **BOLD CAPS** are cited by 15+ sources. Indicators that are associated with contention in the SI literature are underlined. Citations in normal font refer to evaluations or descriptions of SI systems in the field that involve only crops, while underlined citations refer to publications that involve livestock, or both crops and livestock. Citations in *italics* refer to methods papers or overviews that are not specific to any single cropping system.

Indicator	**Field scale metrics**	**Farm / Household metrics**	**Community metrics**
Alternative pest management	Yield effects of alt pest mgt.(Thrupp, 2000;Zhu et al., 2000)		% farmers using alternative pest mgt. (Schreinemachers et al., 2011)
Animal health	Disease incidence (Lusigi, 1995) Farmer-reported condition (Klintenberg et al., 2006) Growth rate(Chigwa et al., 2015;Lusigi, 1995) Mortality rate (McDermott et al., 2010)		
Biological inputs	kg chemical inputs replaced (Powell et al., 2004;Oikeh et al., 2012)	Farm-generated inputs used (Powell et al., 2004; Pretty et al., 2011)	% farmers using biol. Inputs (Fungo et al., 2013)
Biomass production	kg / ha biomass produced (Myaka et al., 2006;Ojiem et al., 2007)		
Conversion efficiency	kg meat/kg grain consumed (Herrero et al., 2010)		
Crop diversity	Crop genotype richness (Zhu et al., 2000) Crop species richness (Valet and Ozier-Lafontaine, 2014)	Crop species richness (Altieri, 1999)	
Cropping intensity	# of crops/unit time (Tilman et al., 2002)	R factor (cropping frequency) (Morse et al., 2002)	
Fodder production	Farmer-assessed range condition(Klintenberg et al., 2006) Primary production of rangeland (Lusigi, 1995) T fodder produced/ha (Boval et al., 2014)		
Fodder quality	Nutritional content of fodder (Lusigi, 1995) Presence of toxins (Bekunda, 2012)	Consumption of legumes (Powell et al., 2004)	
INPUT EFFICIENCY	Efficiency equivalent ratio of nutrient inputs (Valet and Ozier-Lafontaine, 2014) Partial factor productivity of nutrient inputs (Chikowo et al., 2015; Snapp et al., 2010; Tarawali et al., 2011)	Eco-efficiency score; all inputs (Keating et al., 2010; Gadanakis et al., 2015) Energy efficiency analysis; all inputs (*Tyedmers and Pelletier, 2006*)	
Input intensity	Capital intensity in $/ha (Shriar, 2000) Energy intensity in Mj/ha (Giller et al., 1997; *Tyedmers and Pelletier, 2006*) Fertilizer rate in kg/ha (Tittonell et al., 2007)	Intensification index (*Shirar, 2000*)	
Irrigation	mm irrigation water applied (Wani et al., 2003)		% farmers irrigating (Graciana, 2006)
Pest pressure	Farmer reported pest pressure (Snapp and Silim, 2002) # pests/plant or sample (Ndemah et al., 2003; Clermont-Dauphin et al., 2014) # pest species suppressed (Ratnadass and Barzman, 2014) % crop plants damaged (Khan et al., 2008) Weed infestation score (Tittonell et al., 2007)		
RESILIENCE	Relative crop loss due to disaster (Holt-Gimenez et al., 2002) Ability to maintain yield under a range of future scenarios, modeled (*Rosenzweig and Tubelo, 2007*)		
Stocking rate	# animals/ha (Lusigi, 1995) T live weight / ha (Boval et al., 2014)		
WATER EFFICIENCY	kg grain/m^3 water applied / ha (Wani et al., 2003) Yield/mm rainfall (Anderson et al., 2006; Chikowo et al., 2015) Yield/mm evapotranspiration (Anderson et al., 2006)	$ animal products/m^3 evapotranspiration (Descheemaeker et al., 2011) kg total products/m^3 water on land used to grown feed (Kahinda and Masiyandima, 2014)	
YIELD	$ product/ha (Kamanga et al., 2014; Zhu et al., 2000) kg product/ha (ISPC, 2014; Rai et al., 2011) kg product/animal/day (Chigwa et al., 2015; Lusigi, 1995) Land equivalent ratio (Altieri, 1999;Valet and Ozier-Lafontaine, 2014)		
Yield gap	Attainable yield–actual yield (Keating et al., 2010; Wani et al., 2003) Locally attainable yield–actual yield (Tittonell, 2013)		
Yield variability	Coefficient of variation (Morse et al., 2002; Rosenzweig and Tubiello, 2007)		

highest yields actually achieved by farmers in a given region.

3.1.2. *Input efficiency*

Efficient use of inputs for production is a critical goal in SI, and input efficiency is therefore a commonly proposed SI indicator (Keating et al., 2010; Pretty et al., 2011). There are numerous metrics of input efficiency in the literature, appropriate for different purposes. Partial factor productivity is the most commonly used metric, consisting of kg grain yield/kg of a single nutrient (usually N or P) applied (Chikowo et al., 2015; Snapp et al., 2010). For livestock systems a common metric is kg animal product yield/kg dry feed intake (Tarawali et al., 2011). An alternative metric of input efficiency is the eco-efficiency score where the performance of each individual cropping system is contrasted with an eco-efficiency frontier (Keating et al., 2010). This frontier is determined using data on inputs and outputs for a range of cropping systems representative of the region Linear programming

Table 3
SI indicators of economic sustainability with their associated metrics, organized by scale. Indicators in normal font are cited by 3–7 sources, indicators in **bold** are cited by 8–14 sources, and indicators in **BOLD CAPS** are cited by 15+ sources. Indicators that are associated with contention in the SI literature are underlined. Citations in normal font refer to evaluations or descriptions of SI systems in the field that involve only crops, while underlined citations refer to publications that involve livestock, or both crops and livestock. Citations in *italics* refer to methods papers or overviews that are not specific to any single cropping system.

Indicator	Field scale metrics	Farm / Household metrics	Community metrics
AGRICULTURAL INCOME	$ product/ha (Lewis et al., 2011; Zhu et al., 2000) $ product - $ expenses (Kahinda and Masiyandima, 2014; Silici, 2010)	Disposable income (Altieri, 1999) Losses to disaster (Holt-Giménez, 2002) Net income from farming (Sanginga et al., 2003; Twomlow et al., 2006)	
Capital access		Farmer reported change in access to credit (Owenya et al., 2012)	% of households reporting access to credit (Graciana, 2006)
Capital productivity		Benefit / cost ratio (Kamanga et al., 2010; Sanginga et al., 2003) Total factor productivity (Gadanakis et al., 2015)	
Household purchases		Farmer reported change in household consumption (Owenya et al., 2012) % change in household consumption (ISPC, 2014)	
Input access			% farmers reporting access to input (Graciana, 2006) % farmers reporting use of input (Fungo et al., 2013)
Labor intensity	Person time/ha (Schreinemachers et al., 2011; Zimmerer, 2013)		
LABOR PRODUCTIVITY		$ product / person day (Silici, 2010; Twomlow et al., 2006) kg product / person day (Tittonell et al., 2007) Replacement of labor by technology (Powell et al., 2004)	
Market access			Distance to nearest market (Clay et al., 1998; Owenya et al., 2012)
Risk	Prob. that income > expenses (Dorward, 1996; Kamanga et al., 2010) Std. dev. in income/ha (Keating et al., 2010)		
Seed/stock access			% of farmers reporting access constraints (Snapp and Silim, 2002)

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models are then used to identify the existing frontier of optimal net resource use (Gadanakis et al., 2015).

3.1.3. *Water efficiency*

Water use efficiency is employed as a metric of productivity and sustainability in agricultural intensification efforts, particularly in rainfed smallholder systems (Garrity et al., 2010; The Montpelier Panel, 2013). Water use efficiency measures include grain yield/mm rainfall (Anderson et al., 2006; Chikowo et al., 2015), and the increase in crop yield due to irrigation/m^3 irrigation water applied per hectare (Wani et al., 2003). In integrated crop-livestock systems, efficiency of water at the farm scale can be measured as the monetary value of animal products produced per m^3 over total evapo-transpiration from land used to grow feed crops during the growing season (Descheemaeker et al., 2011).

3.1.4. *Animal health*

Animal health is frequently cited as an SI indicator in systems that include livestock (Herrero et al., 2010; McDermott et al., 2010). Animal nutrition, the first dimension, can be measured in terms of livestock growth rate (Chigwa et al., 2015; Lusigi, 1995). Incidence of disease, the second dimension of animal health, can be measured as the proportion of the herd displaying disease indicators (Lusigi, 1995). Finally, mortality rate is sometimes used as a metric (McDermott et al., 2010).

3.2. *Indicators and metrics of economic sustainability*

3.2.1. *Agricultural income*

Several metrics of agricultural income are used in the SI literature (Table 3). Agricultural income is most frequently measured as net income from agriculture (i.e. income from agriculture minus agricultural expenses) (Sanginga et al., 2003; Twomlow et al., 2006). It can also be measured in terms of disposable income, or the agricultural income remaining after expenditures on agricultural inputs and household necessities (Altieri, 1999). Losses of agricultural income due to a natural disaster can be measured by estimating the total market value of crops destroyed by the disaster (Holt-Giménez, 2002). Changes in total agricultural income due to adoption of an agricultural practice can be measured using the benefit/cost ratio (BCR) (Snapp et al., 2010; Tenge et al., 2006).

Table 4

SI indicators of human wellbeing with their associated metrics, organized by scale. Indicators in normal font are cited by 3–7 sources, indicators in **bold** are cited by 8–14 sources, and indicators in **BOLD CAPS** are cited by 15+ sources. Indicators that are associated with contention in the SI literature are underlined. Citations in normal font refer to evaluations or descriptions of SI systems in the field that involve only crops, while underlined citations refer to publications that involve livestock, or both crops and livestock. Citations in *italics* refer to methods papers that are not specific to any single cropping system.

Indicator	Field scale metrics	Farm/Household metrics	Community metrics
Food safety		Environmental Impact Quotient of pesticides used (Schreinemachers et al., 2011)	Toxin concentration of foodstuffs (Bekunda, 2012)
Food security		Days additional food from adopting technology (Garrity et al., 2010)	% farmers reporting reduced food consumption (Lewis et al., 2011)
		Months of available grain stores reported by farmers (Lewis et al., 2011)	
Food self-sufficiency		Calorie production meets household needs (Kamanga et al., 2010)	
		Nutrient production meets household needs (Altieri, 1999; Remans et al., 2013)	
Labor reduction		Reduction in overall time req. to perform agricultural activities (Owenya et al., 2012)	% farmers reporting reduced time needed for ag. activities (Snapp and Silim, 2002)
NUTRITION		Food consumption score (Silici, 2010)	Child stunting rate (Bezner Kerr et al., 2011; Remans et al., 2013)
		Nutrient consumption/ unit agricultural input (The Montpelier Panel, 2013)	Community nutrient demand / community nutrient consumption (Remans et al., 2013)
		Consumption of specific nutrients (Remans et al. 2013)	% farmers reporting access to a healthy diet (Owenya et al., 2012)
Quality of life			% farmers reporting pos. or neg. changes in family health (Morse, 2002)
			% farmers reporting pos. or neg. changes in quality of life (Owenya et al., 2012)
Risk		Prob. that crops meet household calorie demand (Dorward, 1996; Kamanga et al., 2010)	

3.2.2. *Crop value*

Crop value is a commonly cited indicator of economic sustainability in SI systems (ISPC, 2014; Vanlauwe et al., 2014). Several metrics are used to determine the value of crops at the field level. Crop value is most frequently measured as profitability of a crop (income from the crop minus input costs) (Kahinda and Masiyandima, 2014; Silici, 2010). Estimates of labor required to grow a particular crop may be difficult to obtain in smallholder systems. However, factoring in the value of labor is essential to capture the true costs of growing a crop (Kahinda and Masiyandima, 2014).

Table 5

SI indicators of environmental sustainability with their associated metrics, organized by scale. Indicators in normal font are cited by 3–7 sources, indicators in **bold** are cited by 8–14 sources, and indicators in **BOLD CAPS** are cited by 15+ sources. Indicators that are associated with contention in the SI literature are underlined. Citations in normal font refer to evaluations or descriptions of SI systems in the field that involve only crops, while underlined citations refer to publications that involve livestock, or both crops and livestock. Citations in *italics* refer to methods papers or overviews that are not specific to any single cropping system.

Indicator	Field scale metrics	Farm/ Household metrics	Community metrics
Beneficial macro-organisms	Parasitism rate of pests by beneficials (Ndemah et al., 2003		
	Pollination rate (Bommarco et al., 2013)		
	Pollinator diversity (Bommarco et al., 2013)		
	Population of beneficial organism (Clermont-Dauphin et al., 2014; Owenya et al., 2012)		
BIODIVERSITY	Functional diversity (Clermont-Dauphin et al., 2014; Giller et al., 1997)	Genetic diversity as number of varieties planted; Zhu et al., 2000)	Abundance of species of conservation concern (Lewis et al., 2011)
	Presence and abundance of indicator species (Phalan et al., 2011)	Crop diversity dynamics, typological, based on land use over time (Chopin et al. 2015)	Functional diversity (Clermont-Dauphin et al., 2014; Giller et al., 1997)
			Presence and abundance of indicator species (Phalan et al., 2011)
			Landscape-level crop diversity, proportion of farms growing diverse crops (Chopin et al. 2015)
C sequestration	Soil organic carbon mg C/g soil (Demessie et al., 2015; Rosenzweig and Tubiello, 2007), Mg C/ha (Gelaw et al., 2015)	C sequestration rate (*Rosenzweig and Tubelo, 2007*)	Standing tree biomass (Asase et al., 2008)
	Standing tree biomass (Asase et al., 2008)		
Chemical input reduction	kg chemical fertilizer replaced (Altieri, 1999; Oikeh et al., 2012)	Reduction in kg chemicalfertilizer (Fungo et al., 2013) or pesticide (Schreinemachers et al., 2011) applied Reduction in	

(continued on next page)

Table 5 *(continued)*

Indicator	**Field scale metrics**	**Farm/ Household metrics**	**Community metrics**
		number of pesticide applications (Zhu et al., 2000)	
Ecological thresholds	Carrying capacity (Lusigi, 1995)		
Ecosystem services		Replacement value of ecosystem services (Valet and Ozier-Lafontaine, 2014)	
ENVIRONMENTAL IMPACT	Mj inputs/kg of product (*Tyedmers, 2006*) Mj inputs/Mj food energy output (*Tyedmers, 2006*)	$ value of inputs used in system (Gadanakis et al., 2015) Ecological footprint analysis (*Tyedmers, 2006*) EIQ* of pesticides used (Schreinemachers et al., 2011) Lifecycle analysis (*Tyedmers, 2006*)	
EROSION	C-value (erosivity) (Clay et al., 1998)	Volume of gully erosion; area of rill erosion/landslides (Holt-Giménez, 2002)	% farmers reporting erosion (Schmitt-Olabisi, 2012)
	Farmer reported change in soil depth (Swinton, 2000).	Land area with erosion control technologies implemented (Schmitt-Olabisi, 2012; Smith and Plucknett, 1995)	Participatory erosion mapping (Tenge et al., 2006)
	T soil lost/ha/year (Valet and Ozier-Lafontaine, 2014)		
GHG emissions	NH_3 emissions (Klapwijk et al., 2014) T CO_2/kg grain yield (Bellarby et al., 2014) T CO_2/ha (Bellarby et al., 2014)	T c/kg feed digested (Tarawali et al., 2011) T CO_2/kg milk or meat yield (Tarawali et al., 2011)	
NUTRIENT BALANCE	Nutrients applied–nutrient export in grain (Mtengeti et al., 2015) Total nutrient import–total nutrient export (Tittonell 2007) Mineralizable soil N (Myaka et al., 2006) N mineralization rate (Clermont-Dauphin et al., 2014)		Participatory resource mapping (Tittonell et al., 2007) Cycling index (Rufino et al., 2009)

Table 6
SI indicators of social sustainability with their associated metrics, organized by scale. Indicators in normal font are cited by 3–7 sources, indicators in **bold** are cited by 8–14 sources, and indicators in **BOLD CAPS** are cited by 15+ sources. Indicators that are associated with contention in the SI literature are underlined. Citations in normal font refer to evaluations or descriptions of SI systems in the field that involve only crops, while underlined citations refer to publications that involve livestock, or both crops and livestock. Citations in *italics* refer to methods papers or overviews that are not specific to any single cropping system.

Indicator	**Field scale**	**Farm/Household scale**	**Community scale**
Adoption			% of households adopting (Degrande et al., 2013) Adopted on % of total land (Schmitt-Olabisi, 2012) # of hhlds that have adopted (ISPC, 2014; Mhango et al., 2013) # of hectares where adopted (Altieri, 1999)
Animal welfare	Sufficient space for unimpaired health (Fraser, 2008)		
Empowerment		Women's Empowerment in Agriculture Index (Alkire et al., 2013)	% farmers reporting better positioned to solve problems (Rusike et al., 2006)
Equity			Differences in social network connectivity (Hoang, 2006) % households producing profitable cash crop (Graciana, 2006) Uptake and benefits among better off and poorer farmers (Giller, 2011)
FARMER KNOWLEDGE INTEGRATION			% farmers receiving agricultural information from other farmers (Kimaru-Muchai et al., 2013) Use of farmers' criteria for evaluation of SI efforts (Snapp and Silim, 2002; Tenge et al., 2006)
FARMER PARTICIPATION	*No metrics identified*		
Farmer preference			Evaluation of agricultural technologies based on farmers' criteria (Maass et al., 2013; Snapp and Silim,

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Table 6 *(continued)*

Indicator	Field scale	Farm/Household scale	Community scale
			2002) Multi-category scoring of technology (Owenya et al., 2012; Rusinamhodzi et al., 2012) % farmers favoring a technology (Altieri, 1999; Snapp et al., 2010)
Gender equity		Distribution of labor between men and women (Powell et al., 2004)	% project participants or technology users who are women (Degrande et al., 2013; Sanginga et al., 2003)
		Women's Empowerment in Agriculture Index (Alkire et al., 2013)	Women's access to agricultural information (The Montpelier Panel, 2013)
Information access		Connectivity to farmer knowledge network (Hoang et al., 2006)	% farmers reporting knowledge of an SI practice (Degrande et al., 2013)
		Farmer reported access to extension and other sources (Kimaru-Muchai et al., 2013; Owenya et al., 2012)	Test on SI practices (Rusike et al., 2006)
RESILIENCE		Farmer reported adaptation in responses to challenges (Owenya, 2012)	Costs of recovery from disaster (social and monetary) (Béné, 2013)
Resource conflict			Farmer reported conflict intensity (Kisoza, 2014)
Risk			Community risk mapping (Smith et al., 2000)
Social capital		Connectivity to social networks (Hoang, 2006) Membership in organizations (Swinton, 2000) # of social connections (Swinton, 2000)	Community social capital index (Silici, 2010) Social network structure at community level (Hoang, 2006)

3.3. Indicators and metrics of human wellbeing

3.3.1. Food and nutrition security

A subset of authors in the field of SI emphasize the importance of smallholder households being able to meet their own food needs (Altieri, 1999; Remans et al., 2013). This can be measured in terms of the net production of nutrients on the farm relative to the food needs of the farming household. Food production relative to food needs can be measured simply in terms of calories produced by crops versus calorie requirements (Kamanga et al., 2010). Similar analyses have been conducted using a wider range of nutrients, such as protein, calcium and vitamin A (Altieri, 1999; Remans et al., 2013). Human nutrient requirements and food nutrient contents are typically obtained from the literature (Kamanga et al., 2010) or reported by farmers (Remans et al., 2013). The household's ability to meet their own food needs can also be measured in terms of nutrition efficiency, or the consumption of nutrients per unit of agricultural input (The Montpelier Panel, 2013).

3.3.2. Risk

While we have chosen to place risk among indicators of human wellbeing, the concept of risk actually encompasses multiple domains of sustainability. In the context of SI, risk is generally measured as either production risk or perceived risk. Production risk can be quantified as the probability that crops will produce sufficient yield to meet the food or nutritional needs of the household (Dorward, 1996; Kamanga et al., 2010). Production risk can also be assessed economically as the chance that income will exceed expenses (Dorward, 1996), or standard deviation in the economic returns from a cropping system (Keating et al., 2010). Perceived risk was measured by Smith et al. (2000) using participatory risk mapping. Respondents to a survey assessed risk in two stages – first identifying factors they worry about, then assigning a severity to each. This information was used to score the breadth and severity of perceived risks in a community.

3.4. Indicators and metrics of environmental sustainability

3.4.1. Biodiversity

Biodiversity is a broad indicator of SI, and many metrics of biodiversity have been employed. Biodiversity may be measured on the farm itself (Thrupp, 2000) or in the surrounding landscape (Phalan et al., 2011). Functional diversity has been employed as a metric of biodiversity based on the richness and abundance of organisms representing key functional groups in a biological community (Clermont-Dauphin et al., 2014; Giller et al., 1997). The specific functional groups that should be included depend on the type of community under consideration–for example, in a soil community the relevant functional groups might be ecosystem engineers, litter transformers, micro-predators, and decomposer microbes (Giller et al., 1997). In order to measure the impacts of agriculture on biodiversity across many communities, Phalan et al. (2011) recommend measuring biodiversity based on the presence or absence, and abundance, of a number of indicator species. This approach measures alpha diversity (i.e. biodiversity at the local level). In order to determine beta (landscape level) diversity, separate measurements must be conducted for each contiguous area under a distinct type of land use. Other metrics of biodiversity focus on species of special conservation concern, such as population counts of large mammals for a study of intensification effects on an adjacent wildlife reserve (Lewis et al., 2011).

3.4.2. Carbon sequestration

Carbon sequestration is an important indicator of the climate change mitigation potential of agricultural ecosystem (Rai et al., 2011; The Montpelier Panel, 2013). In annual cropping systems consideration is typically restricted to belowground C stocks whereas in perennial systems, C sequestration can be measured as a combination of aboveground and belowground C stocks (Demessie et al., 2015; Rosenzweig and Tubiello, 2007). Aboveground C stocks are typically derived from estimates of standing tree biomass (Asase et al., 2008). To maximize relevance to climate change mitigation, Rosenzweig and Tubelo (2007) recommend calculating the C sequestration rate, a highly data intensive exercise.

3.4.3. Erosion

Metrics of erosion generally focus on the field or farm level, with the rate of erosion expressed in tons of soil lost/ha/year (Valet and Ozier-Lafontaine, 2014). The erosivity of a cropping system (i.e. how prone it is to erosion relative to other cropping systems) can be measured using the C-value (Clay et al., 1998). Alternately, erosion caused by a discreet event such as a hurricane can be measured based on the volume of gully erosion, area of rill erosion, and area of landslides present following the event (Holt-Giménez, 2002). Tenge et al. (2006) present a participatory metric of soil erosion at the community level where a catchment map is drawn by a community assembly, and indicators of erosion are identified. Estimates are validated by the community, and also validated against biophysical measurements taken by researchers.

3.4.4. *Nutrient dynamics*

When nutrients are cycled within an agroecosystem, farmers gain access to fertility that would otherwise have to be supplied via purchased inputs. Therefore, the degree of nutrient cycling within an agricultural system is frequently cited as an indicator of both productivity and environmental sustainability in SI systems (Garrity et al., 2010; Vanlauwe et al., 2014) (Table 5). The most simple metric of internal cycling is the use of farm-generated biological inputs such as leaf litter, manure and compost (Powell et al., 2004; Rufino et al., 2009). The rate of N mineralization in the soil can be used as a metric of internal nutrient cycling (Clermont-Dauphin et al., 2014; Myaka et al., 2006). Some metrics capture multiple stocks and flows of nutrients across the agricultural system, and evaluate the balance between inputs and outputs. In participatory resource mapping, farmers identify all sources, stocks and flows of fertility, into, within, and out of their farming system (Tittonell et al., 2007). This allows farmers to perceive opportunities to increase internal cycling of nutrients.

3.4.5. *Soil biological activity*

Soil biological activity is often proposed as an indicator of ecosystem function in SI (Garrity et al., 2010; Rai et al., 2011). Soil biological activity metrics include soil microbial biomass (Bommarco et al., 2013; Clermont-Dauphin et al., 2014) and soil respiration rate (Clermont-Dauphin et al., 2014). Decomposition is a central biological function in soils, and therefore the decomposition rate is commonly employed as a metric (Asase et al., 2008; Demessie et al., 2015). Additionally, the rate of N mineralization in the soil (part of the decomposition process) is sometimes measured directly (Clermont-Dauphin et al., 2014). Biological N fixation is another critical biological function, particularly in association with legumes and other N fixing plants. One commonly used metric of biological N fixation is the percentage of legume N biomass derived from the atmosphere is one metric of N fixation (Oikeh et al., 2012; Ojiem et al., 2007), but many other metrics are also used in the literature.

3.4.6. *Soil quality*

Soil quality is one of the most commonly cited SI indicators. Soil quality generally refers to the capacity of the soil to support and sustain agricultural production (Clermont-Dauphin et al., 2014; Rai et al., 2011). Water infiltration rate into the soil (Rusinamhodzi et al., 2012; Thierfelder et al., 2013) and the related porosity (Clermont-Dauphin et al., 2014; Rai et al., 2011) are common physical metrics related to soil quality. Soil aggregate stability, which is related to the soil's capacity to resist erosion, can also be employed as a soil quality metric (Clermont-Dauphin et al., 2014).

One of the most commonly employed metrics of soil quality is soil organic matter (Bommarco et al., 2013; Rai et al., 2011), or the closely related metric soil organic carbon (Chikowo et al., 2015; Demessie et al., 2015). Soil organic matter influences the capacity of the soil to retain nutrients and water, as well as multiple other properties. Other chemical properties that are often measured include nutrient status, such as total soil N (Demessie et al., 2015; Gelaw et al., 2015), inorganic N and mineralizable N (Myaka et al., 2006). Other nutrient metrics in the assessment of soil quality include extractable P, Ca, Mg and K (Mhango et al., 2013; Tittonell et al., 2007). The most common metric of nutrient holding capacity is cation exchange capacity (Mhango et al., 2013; Tittonell et al., 2007). Soil pH is also frequently measured in the assessment of soil quality.

3.5. *Indicators and metrics of social sustainability*

3.5.1. *Information access*

Farmers' access to information about agriculture is frequently cited as a sustainability indicator (Rai et al., 2011; Tilman et al., 2002). One metric of farmers' access to information is their level of connectivity within the agricultural knowledge network, consisting of farmers and local experts (Hoang et al., 2006). Access to information about agriculture can also be scored by farmers (Kimaru-Muchai et al., 2013; Owenya et al., 2012). Farmers' knowledge of a specific SI technology or practice can be measured as the percent of farmers reporting knowledge of a practice, and the percent reporting interest in experimenting with the practice, or teaching it to others (Degrande et al., 2013). It can also be measured quantitatively by administering a test to farmers regarding a set of agricultural practices (Rusike et al., 2006).

3.6. *Gender equity*

Organizations promoting SI frequently point out the need to foster gender equity and create opportunities for women (ISPC, 2014; The Montpelier Panel, 2013). Gender equity has been assessed in the SI literature either in an absolute sense, or in relation to a particular SI effort (Table 6). An absolute metric of gender equity, spanning both the household and community levels, is the women's empowerment in agriculture index (WEAI) (Alkire et al., 2013). The WEAI is computed based on a set of farmer-reported indicators where each indicator is assigned a positive or negative value based on survey responses, and a numerical value is calculated using a set of standard weights. Gender equity in a given SI effort can also be measured as the percent of farmers participating in the project or adopting an SI technology who are women (Degrande et al., 2013; Sanginga et al., 2003). Furthermore, equity in the impacts of an SI effort can be reflected in the distribution of labor, or the proportion of SI-related work performed by men relative to that performed by women (Powell et al., 2004).

3.7. *Sustainability frameworks*

Sustainability is a very broad concept, and definitions of sustainability are continually being proposed (Bosshard, 2000; Pretty, 1997). Therefore, it would not be possible to present a single metric of sustainability applicable to any situation. However, a number of authors have proposed frameworks for measuring sustainability of smallholder systems. The most common frameworks for measuring sustainability are based on the “pillars of sustainability” approach (McCune et al., 2011; Steiner et al., 2000). The pillars are individual indicators with associated metrics which are selected to represent different domains of sustainability. Steiner et al., (2000) suggests that pillars be chosen to represent natural capital, social capital and economic capital. However, the approach has also been employed using only biophysical indicators (McCune et al., 2011), or biophysical and economic indicators (Snapp et al., 2010). Regardless of the pillars of sustainability employed, the pillars are depicted as spokes radiating from a central hub, connected by a web diagram. The area and symmetry of the resulting sustainability polygon indicate the sustainability of the system (Steiner et al., 2000). A somewhat different but related approach is the sustainability score employed by Moore et al., (2014). To compute this score, farmers were asked questions related to production, economic sustainability, ecological sustainability, and social sustainability. The researchers assigned a degree of sustainability to each response, and scores were averaged to generate an aggregate sustainability score.

4. Tradeoffs and synergies among SI indicators

Tradeoffs between aspects of sustainability and intensification of agricultural production require close attention, as efforts to achieve large gains in yield can negatively impact production potential in the future through resource exploitation. Intensification of agriculture has been linked to decreased biodiversity (Asase et al., 2008; Phalan et al., 2011), negative impacts on the surrounding environment (Gadanakis et al., 2015; Klapwijk et al., 2014), and increased GHG emissions (Asase et al., 2008; Struik et al., 2014). Conversely, intensification of production on a limited land area can free land for the conservation of species that do not thrive in an agricultural setting (Lewis et al., 2011). Increasing agricultural production in the short term can undermine the long-term basis of productivity through adverse impacts on soil quality, or have the opposite, synergistic effect (Powell et al., 2004; Valbuena et al., 2012). There can be tradeoffs between different types of agricultural productivity, as when dedication of resources to fodder production leads to decreased food security through the displacement of food crops (Herrero et al., 2010). Efforts to increase production can also come into conflict with social values such as the protection of animal welfare (Fraser, 2008; Godfray and Garnett, 2014).

Tittonell (2013) presents a framework for evaluating tradeoffs in SI systems. Tradeoff curves are constructed by plotting values achieved for one SI objective against values achieved for a second objective. The shape of the tradeoff curve reflects the degree of complementarity between these objectives Tradeoff curves are closely related to eco-efficiency frontiers employed in eco-efficiency analysis (Gadanakis et al., 2015; Keating et al., 2010) presented under “input efficiency.” In the analysis of tradeoffs, it is essential to know which properties of the agroecosystem are most important to farmers and other stakeholders. Therefore, Klapwijk (2014) advocates participatory identification and analysis of tradeoffs. In addition, Klapwijk cautions against an excessive focus on optimization, as optimization models are unable to represent all factors that are relevant to the community. Instead, tradeoff curves can be used in a “discussion support” rather than a “decision support” capacity (Klapwijk et al., 2014).

5. Contention regarding SI indicators

While there have been recent calls to define a set of metrics for evaluating SI efforts (Struik et al., 2014; The Montpelier Panel, 2013), there is considerable disagreement in the research community over which indicators and metrics constitute relevant criteria. The meaning of food security in relation to associated concepts such as food equity and distributive justice is contested. Some address food security through gains in production to improve synch with market demand (Keating et al., 2010). Others argue that a focus on market demand privileges those with more purchasing power over those with less, and that an explicit focus on food self-sufficiency and equity is required (Loos et al., 2014). Several SI authors argue that in areas with limited market linkages, farming households' ability to meet their own needs is a key component of food security (Remans et al., 2013; The Montpelier Panel, 2013).

There is also disagreement within the SI literature on the precise meaning of intensification. Some SI theorists equate intensification with increased yield (Godfray and Garnett, 2014). Others define intensification as “more output per unit input”, or the increased efficiency of net resource use (Rai et al., 2011; The Montpelier Panel, 2013). While increased resource use efficiency and improved yield frequently coincide, there are situations in which they do not. For example, deficit irrigation programs generally decrease yield, but greatly increase water use efficiency (Rai et al., 2011).

The meaning of ecological sustainability and the indicators appropriate for its evaluation are debated. Ecological sustainability can be viewed as the reduction of environmental costs associated with each unit of agricultural output with no cap on productivity per-se, an input efficiency approach (Keating et al., 2010). Other authors maintain that impacts must remain bounded by definite ecological thresholds (Shriar, 2000). These thresholds are primarily interpreted as levels of disturbance that would cause the ecological system to transition to an alternate, less productive stable state (Walker et al., 2010).

It should also be kept in mind that – as Bosshard (2000) suggests – sustainability is a discursive paradigm. The precise meaning of sustainability is context dependent, and emerges from the ongoing discussion and engagement of researchers and practitioners working in the field of sustainable agriculture. The structure and goals of any SI effort will depend on the context in which it is carried out, and the actors involved (McDermott et al., 2010; Steiner et al., 2000). According to this view, researchers must continuously define the boundary conditions within which a given set of indicator or metrics is applicable (Tittonell, 2014).

6. Gaps in the SI indicator literature

In this section we assess gaps in the SI literature for each of the domains. Indicators of productivity and economic sustainability are associated with strong collections of metrics, but there are some significant gaps. We were able to locate only a small number of metrics of farmers' access to capital (Graciana, 2006; Owenya et al., 2012), access to agricultural inputs (Fungo et al., 2013; Mhango et al., 2013) and household purchasing power (ISPC, 2014; Owenya et al., 2012). Finally, metrics of market access often focus on distance to the nearest market (Clay et al., 1998; Owenya et al., 2012), and do not consider farmers' ability to competitively participate in markets (The Montpelier Panel, 2013).

Indicators of human wellbeing in SI systems generally lack strong sets of metrics. In the SI literature we found little attention paid to food safety (Bekunda, 2012; Schreinemachers et al., 2011). Food safety concerns appear to be growing within civil society, and it will likely be necessary to develop food safety metrics from the public health literature. Metrics related to quality of life are also scarce. Only a few authors have measured reduction in overall agricultural labor requirements due to SI efforts (Altieri, 1999; Owenya et al., 2012), or impacts on farmers' overall quality of life (Morse et al., 2002). It is also worth noting that none of the cited publications dealing with livestock systems employ metrics of human wellbeing.

Nearly all indicators of environmental sustainability are associated with adequate or strong sets of metrics. One exception is ecological thresholds, which refer to the degree of disturbance that will cause an ecosystem to shift to an alternate, less productive stable state (Walker et al., 2010). The only metric for an environmental threshold that we could locate in the SI literature concerned the carrying capacity of rangeland systems (Lusigi, 1995). To date ecological thresholds have primarily been discussed in the conservation literature, where they are generally conceptualized as the point at which incremental habitat destruction causes a population to go into precipitous decline (Huggett, 2005). It may be advisable to draw on metrics from this literature as we seek to assess ecological thresholds in agricultural systems.

Indicators of social sustainability in SI systems are often associated with few or no concrete metrics in the SI literature. The effects of SI efforts on farmer empowerment have been measured in only a few studies (Alkire et al., 2013; Rusike et al., 2006), and metrics concerning social equity are equally rare (Graciana, 2006; Hoang et al., 2006). Similarly, few metrics of gender equity that go beyond simply counting the women involved in SI efforts have been employed (Alkire et al., 2013; Powell et al., 2004). There are also very few metrics employed to date in the SI literature having to do with social stability. We could only locate a single metric of resource conflict (Kisoza, 2014), though conflict is often a major concern in resource-limited situations. While social metrics are scarce, we should also note that the literature on livestock and crop/livestock systems is rich in farmer-participatory, community-level metrics on subjects ranging from technology preference (Maas et al., 2013) to risk (Smith et al., 2000) to resource conflict (Kisoza, 2014).

Farmer participation and integration of SI efforts with local knowledge systems represent a major gap in the literature (Bosshard, 2000; Kimaru-Muchai et al., 2013). We could find no concrete metrics of the degree of farmer participation in SI efforts (Van de Fliert and Braun, 2002). Criteria for meaningful participation in agricultural research have been defined in the social sciences literature (McDougall and Braun, 2003), and could be used as a basis for quantitative assessment following the model of the WEAI. Addressing this gap in the SI literature is crucial, as farmer participation is central to the SI concept (Pretty, 1997) and there are claims that meaningful participation has been sidelined in the SI agenda (Tittonell, 2014).

Finally, our review of SI indicator literature found that indicators and associated metrics were overwhelmingly static. This allows snap shots in time to be assessed along SI trajectories; however, we think that a more dynamic view is essential.

7. Conclusion

The sustainable intensification literature to date contains a rich array of indicators and metrics for evaluating SI efforts. SI indicators define concepts relevant to sustainable intensification and allow for the articulation of goals in SI efforts. Metrics provide critical tools for assessing progress towards these goals, and evaluating tradeoffs between them. Some often-cited SI indicators currently have few metrics associated with them, particularly in the domain of social sustainability. As the discourse around SI continues and gaps in the literature are filled, it will remain the responsibility of researchers and stakeholders to select indices and metrics that are appropriate to the goals, constraints, and ecological setting of each individual SI effort.

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