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Measuring sustainable intensification in smallholder agroecosystems: A review

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Contents

Abstract

In the sustainable intensification (SI) of smallholder agroecosystems, researchers and farmers collabourate to produce more food on land currently in cultivation, secure wellbeing in the present day, and bolster ecosystem services to sustain agricultural productivity into the future. In recent years there has been debate in the SI literature about the meaning and boundaries SI, accompanied by calls for clearly defined metrics to evaluate SI efforts. In this review, we present the current state of the literature in regards to SI metrics. We first survey the literature to identify key concepts and qualities associated with SI (referred to as SI indicators). We briefly discuss indicators that have been sources of contention in the SI literature, and highlight tradeoffs between certain SI indicators. The bulk of this review focuses on identifying measurable properties (referred to as SI metrics) associated with each SI indicator. We also identify metrics of broader system-level properties such as sustainability and intensification. We conclude by highlighting gaps in the current literature on SI metrics.

Executive summary

The following table presents SI metrics identified in the literature, organized by the SI indicator that they measure and the domain and scale at which they are relevant. We define “indictor” as a quality or concept related to SI, and “metric” as a directly measurable property of an agricultural system. This table includes selected metrics for SI indicators cited by eight or more sources in the literature.

Table 1 – Summary of sustainable intensification (SI) metrics and indicators identified in the literature

Domain	Indicator	Field / Plot scale	Farm / Household scale	Community scale
Productivity	Biological inputs	kg chemical inputs replaced		% farmers using biol. inputs
	Crop diversity	Crop species / genotype richness	Crop species richness	
	Input efficiency	Partial factor productivity	Eco-efficiency score	
	Internal nutrient cycling	N mineralization rate	Use of farm gen. inputs Cycling index	Participatory resource mapping
	Pest pressure	% crop plants damaged # pests / plant or sample		
	Resilience		$ crops lost to disaster	
	Soil quality	Numerous metrics including soil quality indices		
	Water efficiency	yield / mm rainfall kg grain / m^3 water / ha	kg total product / m^3 H_2O	
	Yield	kg or $ product / ha kg product / animal / day		
Economic sustainability	Agricultural income		Net income from farming Benefit / cost ratio	
	Crop value	$ product - $ expenses Benefit / cost ratio		
	Input access			% farmers w/ input access
	Labour productivity		$ product / person day	
	Market access			Distance to nearest market
	Risk	Probability income > expenses Std. dev. in income / ha		
Human wellbeing	Food security		Months avail. grain stores	% farmers reducing food consumption
	Nutrition			Child stunting rate
	Risk		Probability that crops meet household calorie demand	
Environmental sustainability	Biodiversity	Functional diversity	Presence and abundance of indicator species	Abundance of species of conservation concern
	C Sequestration	Soil organic carbon	Standing tree biomass C sequestration rate	Standing tree biomass
	Environmental impact		Environmental Impact Quotient of pesticides used Lifecycle analysis	
	Erosion	T soil lost / ha / year Change in soil depth	Volume of gully erosion Area of rill erosion	% farmers rep. erosion Participatory erosion mapping
	GHG emissions	T CO_2^* / kg grain yield T CO_2^* / ha	T CO_2^* / kg milk or meat yield	
	Resilience		Relative soil loss due to disaster	Functional redundancy in the ecosystem
	Soil biological activity	Microbial biomass Decomposition rate Biological N fixation rate		
	Soil cover / perennial cover	% bare ground Prop. of year vegetated	% tree cover # trees / ha	Prop. area in surrounding landscape perennial. veg.
Social sustainability	Adoption			% of households adopt. Adopted on % of land
	Equity / gender equity		WEAI** Distribution of labour between genders	Uptake & benefits among weather & poorer farmers % female participants

	Farmer knowledge integration			% farmers receiving agricultural information from other farmers
	Farmer participation	Few metrics		
	Information access		Access to farmer know. net. Access to extension	% farmers rep. knowledge of an SI practice
	Resilience		Adaptation in responses to challenges	Costs of recovery from disaster (social & $)
	Risk			Community risk mapping
	Social capital		Membership in groups Connect. to social net.	Social network structure at community level

* CO_2 or CO_2 equivalents
** WEAI = Women's Empowerment in Agriculture Index

Introduction

Food security is threatened by rising food demand, a degraded 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 protect future food security and meet current needs, it will be necessary for researchers and farmers to increase both the productive capacity and sustainability of agriculture. Sustainable intensification (SI) is defined by Pretty et al. (2011) as "producing more output from the same area of land while reducing the negative environmental impacts and at the same time increasing contributions to natural capital and the flow of environmental services." SI relies on collabouration between researchers and farmers to develop locally appropriate agricultural technologies that will meet present and future needs (Pretty, 1997). SI is clearly a tall order, but it may also be an essential project for humanity in the coming decades.

The potential for sustainable intensification of a given agroecosystem depends on the current resource base and level of productivity. In highly technified and input intensive farming systems, yields may already be near the maximum attainable given the constraints of soil, climate and physiology (Keating et al., 2010). In such systems it may be possible to make great improvements in sustainability, but major gains in productivity may be difficult to achieve. On the other hand, many resource-limited smallholder farms, including both crop and livestock systems, have a great potential for increased yields (Herrero et al., 2010; Pretty et al., 2011). Given that many smallholder farmers suffer from malnourishment and rely largely on their own agricultural production for survival (Garrity et al., 2010), sustainable intensification of smallholder systems has the potential to increase human wellbeing in the present day while strengthening the foundations of future food security.

Though there is widespread agreement around the need to increase productivity and sustainability in smallholder agroecosystems, the term sustainable intensification has been a point of some contention in the literature. Sustainable intensification was first presented as a collabourative project between researchers and farmers in which efforts to increase food production would be balanced with efforts to secure environmental, social and economic sustainability while increasing present-day equity and wellbeing (Pretty, 1997). In the opinion of some authors, the term sustainable intensification has come to be used in a productionist sense, with concerns for sustainability and equity taking second place (Loos et al., 2014; Tittonell, 2014). Given the tension surrounding the term sustainable intensification, it is important to carefully define what SI is, and what it is not.

In a discussion of sustainability in agriculture, Bosshard (2000) points out that sustainability is a discursive paradigm. In other words, 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. Likewise sustainable intensification. The structure and goals of any SI effort will depend on the context in which it is carried out, and the actors involved in implementing it (McDermott et al., 2010; Steiner et al., 2000). However, in order to preserve the meaning of sustainable intensification as a concept, 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 elabourate appropriate metrics of sustainable intensification 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).

In this review, we aim to provide a foundation for efforts to define and measure sustainable intensification in smallholder agroecosystems. We present a broad range of concepts that have been associated with SI in the literature, and metrics that have been used to evaluate SI systems. Our goal is not to provide a precise definition of sustainable intensification, nor is it to provide an exhaustive and final catalogue of acceptable SI metrics. Rather, we aim to provide a resource base that reflects the current state of thinking on sustainable intensification. We hope that this review will aid future efforts to develop context-appropriate definitions of sustainable intensification in smallholder systems and measure progress towards the objectives of SI.

A note on terminology:
In this report, we assign specific meanings to the terms “indicators” and “metrics.” We use the term “indictor” 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, biodiversity is a commonly cited SI indicator. However, biodiversity refers to a wide range of measurable properties. Among them are species richness, relative abundance of species, and functional diversity. We refer to these latter properties as metrics.

Methods

We searched the scientific literature using Web of Science and Google Scholar for references to sustainable intensification and smallholder systems. Additionally, we searched for works that employ related terms, such as 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 community scales. We also included some works that do not explicitly reference SI or related terms, but do focus on both intensification and sustainability in smallholder systems. Works referenced in this review include peer-reviewed journal articles, academic books and book chapters, academic conference proceedings, and public reports by well-known international agricultural research organizations.

In our search of the SI literature we gathered three general classes of publications: works defining SI and presenting a range of SI indicators, works focused on describing concrete metrics appropriate to SI systems, and works describing and evaluating SI efforts. The latter class was by far the largest, including an extensive array of primary research articles and case studies focusing on smallholder SI efforts.

To narrow down this list, we applied the following criteria for inclusion of primary research articles and case studies in this review:

- The study must have been conducted in a smallholder system. This includes on-farm research trials, but excludes trials performed on agricultural stations.
- The study must explicitly evaluate both productivity and at least one aspect of sustainability.
- The study must employ and clearly describe SI-relevant metrics. These metrics must go beyond simply crop yield, or simply adoption of a technology.
- The study must be of good scientific merit and include adequate citations.

SI indicators identified in the literature

The following table presents SI indicators identified in the literature, organized by SI domain and 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.

Table 2 – SI indicators

Domain	**Field/Plot scale**	**Farm/Household**	**Community**
Productivity	Adaptive capacity Alternative pest mgt. **Biological inputs** Biomass production **Crop diversity** Cropping intensity Fodder production **INPUT EFFICIENCY** Input intensity **INTERN. NUT. CYCLING** Irrigation **Pest pressure** **SOIL QUALITY** Stocking rate **WATER EFFICIENCY** **YIELD** Yield gap Yield variability	Chemical input reduction **Crop diversity** Cropping intensity Fodder quality **INPUT EFFICIENCY** **INTERNAL NUT. CYCLING** **RESILIENCE** **WATER EFFICIENCY**	Alternative pest management **Biological inputs** **INTERNAL NUTRIENT CYCLING** Irrigation
Economic Sustainability	**Crop value** Labor intensity **Risk**	**AGRICULTURAL INCOME** Capital access Capital productivity Household purchases **LABOR PRODUCTIVITY**	Capital access **Input access** **Market access** Seed / stock access
Human wellbeing		Food safety **Food security** Food self-sufficiency Labor reduction **Risk**	Food safety **Food security** Labor reduction **NUTRITION** Quality of life Water quality
Environmental sustainability	Beneficial organisms **BIODIVERSITY** **C sequestration** Chemical input reduction Ecological thresholds **ENVIRON. IMPACT** **EROSION** **GHG emissions** Nutrient balance Nutrient export **Soil biological activity** **Soil cover**	**C sequestration** **ENVIRONMENTAL IMPACT** **EROSION** **GHG emissions** **Perennial cover** **RESILIENCE**	**BIODIVERSITY** **C sequestration** **EROSION** Nutrient balance **Perennial cover** **RESILIENCE**
Social sustainability	Animal welfare	Empowerment **Gender equity** **Information access** **RESILIENCE** **Social capital**	**Adoption** Empowerment **Equity** **FARMER KNOWLEDGE INTEG.** **FARMER PARTICIPATION** Farmer preference **Gender equity** **Information access** **RESILIENCE** Resource conflict **Risk** **Social capital** Ways of life

Contentions regarding SI indicators

While there is broad consensus regarding many indicators of sustainable intensification, some indicators have been the focus of controversy in the SI literature. One area of contention has been the meaning of food security in relation to associated concepts such as food equity and distributive justice. On one hand, some SI theorists propose to address food security by increasing food production, thus bringing production at the national or global scale into synch with market demand (Keating et al., 2010). Others argue that a simple focus on market demand privileges those with more purchasing power over those with less, and that an explicit focus on food equity is instead required (Loos et al., 2014). This debate also relates to the concept of food self-sufficiency. From a market-oriented perspective, net food production takes precedence over farmers' ability to supply their own nutritional needs. However several SI authors argue that, in smallholder systems with limited market linkages, farming households' ability to meet their own needs is indeed 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). In situations where water resources are under extreme pressure, water efficiency may be the paramount concern in intensification efforts. Additionally, Rai et al. (2011) argue that in rainfed systems with high climatic variability, it may be most appropriate to define intensification as reduction in risk faced by farmers rather than defining it as increased yield.

We should also point out that some authors have used the term intensification to denote input intensity or the use of technified farming practices (Giller et al., 1997). This usage has been uncommon in the recent SI literature, however, and current views of intensification appear to focus on yield or resource use efficiency.

Additionally, there has been disagreement over the meaning of ecological sustainability and the indicators appropriate to it. On one hand, sustainability can be viewed as the reduction of environmental costs associated with each unit of agricultural output (Keating et al., 2010). This view puts no cap on productivity per-se, so long as it can be achieved with minimal environmental impact. On the other hand, some authors maintain that in order for an agricultural system to remain sustainable, the impacts of the system must remain bounded by definite ecological thresholds (Shriar, 2000). These thresholds, or tipping points, refer to levels of disturbance which will cause an ecological system to transition to an alternate, less productive stable state (Walker et al., 2010). These contrasting views influence whether SI efforts are assessed in terms of their input efficiency, or assessed based on how their environmental impacts relate to ecological thresholds.

Tradeoffs between SI indicators

This should not be considered a comprehensive list of tradeoffs. Rather, it reflects tradeoffs which received particular emphasis in the literature. Sources for specific tradeoffs are indicated in the main table by numerals, and the corresponding references are provided in the columns below.

Table 3 – Tradeoffs between SI indicators identified in the literature

	Animal health	Capital productivity	Fodder product.	Market access	Stocking rate	Yield
Animal health						2
Animal welfare	3					3; 6
Biodiversity						1; 6; 10
C sequestration						1
Environ. Impact						4; 9
Food security			7			
GHG emissions		13				
Nutrition						6
Resource conflict				8	8	
Soil quality			9; 11; 15			9; 12
Water efficiency						14
Water quality						9

References for specific tradeoffs:

1: (Asase et al., 2008)	6: (Godfray and Garnett, 2014)	11: (Powell et al., 2004)
2: (Chigwa et al., 2015)	7: (Herrero et al., 2010)	12: (Snapp and Silim, 2002)
3: (Fraser, 2008)	8: (Kisoza, 2014)	13: (Struik et al., 2014)
4: (Gadanakis et al., 2015)	9: (Klapwijk et al., 2014)	14: (Thierfelder et al., 2013)
5: (Garnett et al., 2013)	10: (Phalan et al., 2011)	15: (Valbuena et al., 2012)

SI indicators and associated metrics

Indicators in *italics* have limited metrics associated with them or are lacking metrics entirely. Indicators that are underlined are associated with contention in the SI literature. SI metrics and any contention associated with them are described in "Descriptions of SI metrics".

Table 4 – SI indicators of productivity with their associated metrics, organized by scale

Indicator	**Field scale metrics**	**Farm / Household metrics**	**Community metrics**
Adaptive capacity	Maintain yield under future scenarios		
Alternative pest management	Yield effects of alt pest mgt.		% farmers using alt pest mgt.
Animal health	Disease incidence Farmer-reported condition Growth rate Mortality rate		
Biological inputs	kg chemical inputs replaced		% farmers using biol. inputs
Biomass production	kg / ha biomass produced		
Crop diversity	Crop genotype richness Crop species richness	Crop species richness	
Cropping intensity	# of crops / unit time	R factor (cropping frequency)	
Fodder production	Farmer-assessed range condition Primary production of rangeland T biomass produced / ha		
Fodder quality		Consumption of legumes Nutritional content of fodder Presence of toxins	
Input efficiency	Efficiency equivalent ratio Partial factor productivity	Eco-efficiency score Energy efficiency analysis	
Input intensity	Capital intensity in $ / ha Energy intensity in Mj / ha Fertilizer rate in kg / ha		
Internal nutrient cycling	Mineralizable soil N N mineralization rate	Cycling index Farm-generated inputs used	Participatory resource mapping
Irrigation	mm irrigation water applied		% farmers irrigating
Pest pressure	Farmer reported pest pressure # pests / plant or sample # pest species suppressed % crop plants damaged Weed infestation score		
Resilience (see also environ. and social metrics)		$ crops lost due to disaster	
Soil quality	Numerous metrics of physical, chemical and biological properties Soil quality indices		
Stocking rate	# animals / ha T live weight / ha		
Water efficiency	kg grain / m^3 water / ha Relative water use efficiency Yield / mm rainfall Yield / mm ET^*. water	$ animal products / m^3 evapotranspiration from kg total products / m^3 water land used to grow feed	
Yield	$ product / ha kg product / ha kg product / animal / day kg meat / kg grain consumed Land equivalent ratio		
Yield gap	Actual yield – attainable yield		
Yield variability	Coefficient of variation		

Indicators in *italics* have limited metrics associated with them or are lacking metrics entirely. Indicators that are underlined are associated with contention in the SI literature. SI metrics and any contention associated with them are described in "Descriptions of SI metrics".

Table 5 – SI indicators of economic sustainability with their associated metrics, organized by scale

Indicator	Field scale metrics	Farm / Household metrics	Community metrics
Agricultural income		Benefit / cost ratio Disposable income Losses to disaster Net income from farming	
Capital access		Farmer reported change in access to credit	% of households reporting access to credit
Capital productivity		Benefit / cost ratio Total factor productivity	
Crop value	Benefit / cost ratio $ product / ha $ product - $ expenses		
Household purchases		Farmer reported change in household consumption % change in household consumption	
Input access			% farmers reporting access to input % farmers reporting use of input
Labor intensity	Person time / ha		
Labor productivity		$ product / person day kg product / person day	
Market access			Distance to nearest market
Risk (also see social and human wellbeing metrics)	Prob. that income > expenses Std. dev. in income / ha		
Seed / stock access			% of farmers reporting access constraints

Indicators in *italics* have limited metrics associated with them or are lacking metrics entirely. Indicators that are underlined are associated with contention in the SI literature. SI metrics and any contention associated with them are described in “Descriptions of SI metrics”.

Table 6 – SI indicators of human wellbeing with their associated metrics, organized by scale

Indicator	**Field scale metrics**	**Farm / Household metrics**	**Community metrics**
Food safety		Environmental impact quotient of pesticides used	Toxin concentration of foodstuffs
Food security (also see nutrition metrics)		Days additional food from adopting technology Months of available grain stores reported by farmers	% farmers reporting reduced food consumption
Food self-sufficiency		Calorie production meets household needs Nutrient consumption / unit agricultural input Nutrient production meets household needs	
Labor reduction		Reduction in overall time req. to perform agricultural activities	% farmers reporting reduced time needed for ag. activities
Nutrition		Food consumption score	Child stunting rate Comm. nutrient demand / comm. nutrient consumption % farmers reporting access to a healthy diet
Risk (also see economic and social metrics)		Prob. that crops meet household calorie demand	
Quality of life			% farmers reporting pos. or neg. changes in family health % farmers reporting pos. or neg. changes in quality of life
Water quality			Bacterial count of water source NO_3 concentration of water

Indicators in *italics* have limited metrics associated with them or are lacking metrics entirely. Indicators that are <u>underlined</u> are associated with contention in the SI literature. SI metrics and any contention associated with them are described in "Descriptions of SI metrics".

Table 7 – SI indicators of environmental sustainability with their associated metrics, organized by scale

Indicator	Field scale metrics	Farm / Household metrics	Community metrics
Beneficial macro-organisms	Parasitism rate of pests by beneficials Pollination rate Pollinator diversity Population of beneficial organism		
Biodiversity	Functional diversity	Functional diversity Presence and abundance of indicator species	Abundance of species of conservation concern Functional diversity Presence and abundance of indicator species
C sequestration	Soil organic carbon Standing tree biomass	C sequestration rate Soil organic carbon Standing tree biomass	Standing tree biomass
Chemical input reduction	kg chemical input replaced	Reduction in kg inputs applied Reduction in # input applications	
Ecological thresholds	Carrying capacity		
<u>Environmental impacts</u> (see also Water quality and GHG emissions)	Mj inputs / kg of product Mj inputs / Mj food energy output	$ value of inputs used in system Ecological footprint analysis Environmental impact quotient of pesticides used Lifecycle analysis	
Erosion	C-value (erosivity) Farmer reported change in soil depth T soil lost / ha / year	Volume of gully erosion Area of rill erosion / landslides Land area with erosion control technologies implemented	% farmers reporting erosion Participatory erosion mapping
<u>GHG emissions</u>	NH_4 emissions T CO_2 / kg grain yield T CO_2 / ha	T CH_4 / kg feed digested T CO_2 / kg milk or meat yield	
<u>Nutrient balance</u>	Nutrients applied – nutrient export in grain Total nutrient import – total nutrient export		Participatory resource mapping
Nutrient export	N removed for use as fodder NH_4 volatilization NO_3 leeching		
Perennial cover		# trees / ha % cover at canopy and bush level % tree cover	Deforestation rate Prop. area in surrounding landscape perennially vegetated
<u>Resilience</u> (see also productive and social metrics)		Relative soil loss due to disaster	Functional redundancy in the ecosystem
Soil biological activity	Biological N fixation rate Decomposition rate Microbial biomass N mineralization rate Soil respiration		
Soil cover	% bare ground Prop. of year vegetated		

Indicators in *italics* have limited metrics associated with them or are lacking metrics entirely. Indicators that are underlined are associated with contention in the SI literature. SI metrics and any contention associated with them are described in "Descriptions of SI metrics".

Table 8 – SI indicators of social sustainability with their associated metrics, organized by scale

Indicator	Field scale	Farm / Household scale	Community scale
Adoption			% of households adopting Adopted on % of total land # of hhlds that have adopted # of hectares where adopted
Animal welfare	Sufficient space for unimpaired health		
Empowerment		Women's Empowerment in Agriculture Index	% farmers reporting better positioned to solve problems
Equity			Differences in social network connectivity % households producing profitable cash crop Uptake and benefits among better off and poorer farmers
Farmer knowledge integration			% farmers receiving agricultural information from other farmers Use of farmers' criteria for evaluation of SI efforts
Farmer participation			Full participation in R&D, extension, and impact eval.
Farmer preference			Farmers' criteria for evaluation of agricultural technologies % farmers favoring a technology
Gender equity		Distribution of labor between men and women Women's Empowerment in Agriculture Index	% project participants or technology users who are women
Information access		Connectivity to farmer knowledge network Farmer reported access to extension and other sources	% farmers reporting knowledge of an SI practice Scores on test of knowledge about specific SI practice
Resilience (see also productive and environmental metrics)		Farmer reported adaptation in responses to challenges	Costs of recovery from disaster (social and monetary)
Resource conflict			Farmer reported conflict intensity
Risk (see also economic and human wellbeing metrics)			Community risk mapping
Social capital		Connectivity to social networks Membership in organizations # of social connections	Community social capital index Social network structure at community level
Ways of life	*No metrics identified*		

Descriptions of SI metrics

Adaptive capacity (limited metrics)

Several SI scholars have highlighted adaptive capacity as an indicator of sustainability in intensifying agroecosystems (Pretty et al., 2011; Walker et al., 2010). However, there are few metrics of adaptive capacity employed in the literature. The capacity to adapt to climate change has been measured based on cropping systems' capacity to achieve satisfactory yield under future climate scenarios (Rosenzweig and Tubiello, 2007). Crop / soil / atmosphere models are run under meteorological conditions modified to reflect future climate scenarios. These models can simulate the yield effects of simple adaptations such as altered planting time or the use of crop varieties with different physiological traits. However, this metric is only appropriate for predicting the effects of simple adaptations, and is less suitable for total reconfigurations of the cropping system. It is also best suited to predicting the effects of altered mean climate variables (such as increased average temperature), and less well suited to predicting the effects of increased climatic variability.

Adoption (adequate metrics)

The rate of adoption of an agricultural technology or practice is frequently used to indicate the social sustainability of SI efforts (Steiner et al., 2000). Adoption rate can be measured in terms of the % of total farming households in a given area that have adopted a practice or technology (Degrande et al., 2013), or the percent of total land on which the technology has been adopted (Schmitt-Olabisi, 2012). In addition, some authors report adoption as a raw figure, i.e. the total number of farmers who have adopted the technology (ISPC, 2014; Mhango et al., 2013) or the number of hectares on which the technology has been implemented (Altieri, 1999).

Agricultural income (strong metrics)

Several metrics of agricultural income are used in the SI literature. 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 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). The benefit / cost ratio contrasts the total costs of a new practice (including the cost of labour) with the annual financial benefits that the practice yields. Calculation of the BCR requires data on the total costs of a new practice (including the cost of labour), and the total annual benefits that it yields.

Alternative pest management (adequate metrics)

Alternative (or non-chemical) pest management is seen by many as a core component of SI efforts (Rai et al., 2011; Thrupp, 2000). Alternative pest management can be measured as the percent of farmers who report using non-chemical methods of pest control (Schreinemachers et al., 2011). Alternately, the effectiveness of alternative pest management interventions can be measured as the number of pest species noticeably suppressed by the intervention (Ratnadass and Barzman, 2014), or as increases in yield attributable to the intervention (Thrupp, 2000; Zhu et al., 2000).

Animal health (strong metrics)
Animal health is frequently cited as an SI indicator in systems that include livestock (Herrero et al., 2010; McDermott et al., 2010). Two principal dimensions of animal health are used as metrics of SI. Animal nutrition, the first dimension, can be measured in terms of livestock growth rate in g / day (Chigwa et al., 2015; Lusigi, 1995). Alternately, farmers can score livestock condition based on a set of standard photos (Klintenberg et al., 2006). Incidence of disease, the second dimension of animal health, can be measured as the proportion of the herd displaying disease indicators (Lusigi, 1995). The specific indicators employed will vary based on the livestock species and the diseases prevalent in the region. Finally, mortality rate is sometimes used as a metric of animal health (McDermott et al., 2010). Mortality rate captures the dimensions of animal nutrition and disease simultaneously.

Animal welfare (limited metrics; contention)
While animal welfare is often referenced as an important SI indicator (Bosshard, 2000; Godfray and Garnett, 2014), metrics of animal welfare are both scarce and disputed. This is due in part to disagreements over what the term "animal welfare" actually implies. Fraser (2008) points out that animal welfare is commonly conceptualized in three ways: as the integrity of livestock animals' bodily functions, as the affective state of livestock animals, and as the animals' ability to perform the full range of actions that they would perform under minimally intensive management. These conceptions of animal welfare can be contradictory, as when conditions that allow animals to perform their full range of behaviors (i.e. open pasturing) make them more vulnerable to attack by predators. Fraser proposes, as a minimal standard of animal welfare, that livestock animals be given sufficient space to allow unimpaired physical health. If this condition is not met, animal welfare is compromised under all three welfare concepts.

Beneficial macro-organisms (adequate metrics)
Some commentators on SI point to the presence or action of beneficial macro-organisms, particularly beneficial insects, as an indicator of sustainability in SI systems (Ratnadass and Barzman, 2014). Metrics of beneficial organisms generally focus on a particular organism or group of organisms. The earthworm population / m2 of topsoil has been used as a metric of beneficial organisms involved in nutrient cycling (Clermont-Dauphin et al., 2014; Owenya et al., 2012). Likewise, the populations of natural enemies of crop pests can be estimated based on the number captured per sample (Clermont-Dauphin et al., 2014). For communities of crop pollinators, the richness of pollinator species visiting crop plants is commonly measured (Bommarco et al., 2013).

Other metrics of beneficial organisms focus on their function in agricultural ecosystems. The activity of beneficial organisms that parasitize crop pests can be measured based on the parasitism rate within the population of pests (Ndemah et al., 2003). Additionally, crop pollination can be estimated based on the visitation rate of pollinators to crop plants (Bommarco et al., 2013).

Biodiversity (adequate metrics)
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 in communities which provide ecosystem services, such as soil communities (Clermont-Dauphin et al., 2014; Giller et al., 1997). Indices of functional diversity are based on the richness and abundance of organisms representing key functional groups in a biological community. The specific functional groups that should be included in an index of functional diversity depend on the type of community under consideration – for example, in a soil community the relevant functional groups might be

ecosystem engineers, litter transformers, micropredators, 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 of a number of indicator species, and the relative abundance of each species. A broad range of indicator species must be selected to represent the wider species assemblage. This approach measures alpha diversity (i.e. biodiversity at the local level). Therefore 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. Lewis et al. (2011) used population counts of large mammals when evaluating the impacts of intensification efforts on biodiversity in an adjacent wildlife reserve.

Biological inputs (adequate metrics)

Increased use of biological inputs such as manure and compost is sometimes cited as an indicator of sustainable intensification (The Montpelier Panel, 2013). The most simple metric of biological inputs is the percent of farmers who report applying biological inputs to their fields (Fungo et al., 2013). Biological inputs can also be measured in terms of the nutrients that they replace. Input replacement is measured as the amount of chemical fertilizer necessary to generate the same crop response as a given biological input (Powell et al., 2004). This can be expressed in kg N / ha replaced (Oikeh et al., 2012). In order to calculate N replacement, it is necessary to obtain an N response curve (crop yields under varying levels of N input), as well as yields from systems where biological alternatives are used.

Biomass production (adequate metrics)

Biomass production is a critical measure of agricultural productivity and the net primary productivity of the agroecosystem (ISPC, 2014). Biomass production is typically expressed as kg/ha of aboveground non-grain biomass produced (Myaka et al., 2006; Ojiem et al., 2007). As different biomass fractions may differ greatly in their nutrient contents and ease of decomposition, biomass yield may be divided into fractions such as leaves, stems and pods, or piths, husks and stover (Myaka et al., 2006).

C sequestration (strong metrics)

Carbon sequestration is an important indicator of the climate change mitigation potential of agricultural ecosystem (Rai et al., 2011; The Montpelier Panel, 2013). C sequestration is most frequently measured in terms of carbon stocks. In annual cropping systems, consideration is typically restricted to belowground C stocks. Belowground C stocks are determined by measuring soil organic carbon (SOC) reported in mg / g soil (Demessie et al., 2015; Rosenzweig and Tubiello, 2007). When soil bulk density is also obtained, this figure can be converted to Mg C / ha (Gelaw et al., 2015). In perennial cropping systems, C sequestration can be measured as a combination of aboveground and belowground C stocks. 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. This is metric is highly data intensive, and requires full accounting of carbon inputs, sinks and outputs in the farming system. Non carbon greenhouse gasses such as CH_4 and N_2O are expressed as C equivalents based on their global warming potential.

Capital access (limited metrics)

Farmers' access to capital is occasionally cited as an indicator of the economic sustainability of SI systems (Vanlauwe et al., 2014). Credit access is generally used as a metric of access to capital. This can be measured as the percent of farmers who report being able to obtain some form of credit (Graciana, 2006). It can also be measured qualitatively by contrasting farmers' perception of how easy it is to obtain credit now, versus how easy it was to obtain in the past (Owenya et al., 2012).

Capital productivity (adequate metrics; contention)

Capital productivity, or the total value generated by a given input of capital, can be used as an indicator of economic sustainability (Kamanga et al., 2010; Keating et al., 2010). Capital productivity can be measured in several ways. The most straightforward metric is the benefit / cost ratio. This can be expressed as kg crop obtained / $ spent on agricultural inputs (Kamanga et al., 2010), or as $ crop sales obtained / $ spent on inputs (Sanginga et al., 2003; Snapp et al., 2010).

Total factor productivity is another approach to measuring capital productivity. In order to compute total factor productivity, all inputs and outputs of a farming system must be monetized (Gadanakis et al., 2015). Total factor productivity is then calculated as the ratio of total outputs to total inputs. This metric has been criticized for its dependence on input and output prices, which can be highly volatile (ISPC, 2014; Shriar, 2000). Therefore, it can be difficult to tell whether changes in total factor productivity are due to fluctuations in the markets, or due to changes in the agricultural system.

Chemical input reduction (adequate metrics)

Reduction of chemical inputs applied to agricultural systems is occasionally used as an indicator of sustainability in SI efforts (Schreinemachers et al., 2011). Input reduction is often measured as the reduction in chemical input use at the farm level when a biologically-based alternative is adopted. This may be a reduction in fertilizer rates among farmers applying manure to their fields (Fungo et al., 2013), reduction in $ spent on pesticides among farmers taking part in a sustainability program (Schreinemachers et al., 2011), or reduction in the frequency of pesticide applications among farmers participating in an alternative pest management experiment (Zhu et al., 2000). Reduction of chemical inputs can also be measured as the input replacement value of a technology or practice. Fertilizer replacement value is the amount of a single chemical input that would be necessary to achieve yields equivalent to those achieved by the alternative technology (Altieri, 1999; Oikeh et al., 2012).

Crop diversity (adequate metrics)

Crop diversity is frequently cited as an indicator of productivity and resilience in agroecosystems (Doré et al., 2011; Rai et al., 2011). Crop diversity can be measured in terms of species richness or genotype richness. Crop species richness is the number of species planted within a given cropping system at a given time (Valet and Ozier-Lafontaine, 2014). Genotype richness, on the other hand, is the number of distinct crop genotypes or varieties simultaneously planted in a given cropping system (Zhu et al., 2000). Crop species richness is also calculated at the scale of the entire farm (Altieri, 1999). Additionally, both crop species richness and genotype richness can be calculated across a timespan of several seasons, rather than at a particular moment, to obtain metrics of crop diversity across time (Tilman et al., 2002).

Crop value (strong metrics)

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 sometimes measured as a raw value without consideration of input expenses, and reported as the $ value of the crops produced / ha (Lewis et al., 2011; Zhu et al., 2000). Crop value is most frequently measured as profitability of a crop (income from the crop minus input costs) (Kahinda and Masiyandima, 2014; Silici, 2010). Crop value can also be expressed as a benefit / cost ratio (income from the crop / input costs including costs of labour) (Kamanga et al., 2014; Snapp et al., 2002). Estimates of labour required to grow a particular crop may be difficult to obtain in smallholder systems. However, factoring in the value of labour is essential to capture the true costs of growing a crop (Kahinda and Masiyandima, 2014).

Cropping intensity (adequate metrics)

Cropping intensity represents one intensification pathway in agroecosystems – growing crops with increased frequency on the same land (Tilman et al., 2002). At the field level, cropping intensity can be measured as the number of crops grown within a given span of time (Tilman et al., 2002). Cropping intensity can also be measured at the farm level using the R factor (Morse et al., 2002). This is computed by determining the % of growing seasons that each field was in cultivation during the last 10 years, and then averaging across all fields.

Ecological thresholds (limited metrics)

Environmental thresholds can be thought of as “tipping points”, or conditions under which an ecological system shifts from a more productive stable state to an alternate, less productive stable state (Walker et al., 2010). Commentators on SI have noted that sustainability requires that we identify and do not exceed environmental thresholds (Lal and Stewart, 2014; Walker et al., 2010). However, there are currently few metrics of environmental thresholds in the SI literature. One established environmental threshold metric, used primarily in the study of grazing systems, is carrying capacity (Lusigi, 1995). This is the maximum stocking density at which forage plants are able to fully regenerate. Measurement of the carrying capacity of rangelands requires that climatic variability be taken into account, as forage plants will regenerate more slowly under dry conditions.

Empowerment (limited metrics)

Empowerment of smallholder farmers, and particularly woman farmers, is cited by some authors as an indicator of the social sustainability of SI efforts (Loos et al., 2014; McDermott et al., 2010). However, empowerment is a broad term, and discreet metrics of empowerment are scarce. The women’s empowerment in agriculture index (WEAI) is one quantitative metric of empowerment (Alkire et al., 2013). The WEAI is computed based on a set of farmer-reported indicators including input into production decisions, autonomy in production, ownership of assets, purchase, sale or transfer or assets, access to and decisions about credit, control over use of income, membership in groups, comfort speaking in public, workload and leisure time. 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.

Additional metrics focus on increased empowerment among smallholder farmers due to an intervention. Increased empowerment has been measured as the % of farmers who report either that they are in a better position to solve agricultural problems on their own, or that they have made new demands on extension staff (Rusike et al., 2006).

Environmental impact (adequate metrics, contention)

Environmental impact is very frequently cited as a factor which must be reduced in sustainable intensification efforts (Pretty, 1997; Tyedmers and Pelletier, 2006). However, this is a very broad concept, and there are entire fields of science devoted to measuring environmental impact. Several principal metrics are used in the SI literature, though this should not be considered an exhaustive list by any means.

Perhaps the most simple way to measure environmental impact is to assume that it is proportional to the cost of inputs used in the system. This approach is taken by some authors employing the eco-efficient agriculture approach, who employ the ratio of inputs required / product produced as a metric of both input efficiency and environmental impact (Gadanakis et al., 2015). This approach has been criticized on the grounds that the cost of inputs does not always reflect how renewable they are, or their relative impact on the environment (Struik et al., 2014).

Tyedmers (2006) describes several alternative metrics that can be used to broadly assess the environmental impact of agricultural systems. Energy analysis is based on the ratio of the energy used in production / the energy contained in products. This requires a thorough accounting of the energy contained in all direct and indirect inputs. The results of energy analysis can be expressed in Mj inputs / kg of product, or as Mj inputs / Mj food energy output. Ecological footprint analysis, an alternate metric, measures the environmental cost of an activity as the area of functioning ecosystem that would be required to replace the ecosystem services that the activity destroys. Finally, lifecycle analysis measures the environmental cost of an activity in terms of its contribution to environmental problems, assessing impacts across all stages of production, distribution and consumption.

Many additional metrics of environmental impact focus on environmental damage from a discreet set of inputs or practices. Environmental damage due to pesticide use can be estimated using the Environmental Impact Quotient, a scoring system based on each agrochemical's potential to harm humans and ecosystems, along with the rate and frequency of pesticide application and the concentration of each active ingredient in the mixtures applied (Schreinemachers et al., 2011). For metrics of environmental impact having to do with greenhouse gasses and water quality, see "Greenhouse gas emissions" and "Water quality."

Equity (limited metrics)

Social equity at the community level refers to the distribution of resources and rights within a community, with particular reference to the evenness of distribution (Loos et al., 2014). Equity can be considered an essential part of social sustainability, but it is rarely taken into account in evaluating SI efforts. Graciana (2006) presents one metric of equity in smallholder communities. The percent of households involved in production of a capital intensive, profitable cash crop (sugarcane) was used as an indicator of social equity within the community. The validity of this indicator was supported based on correlations between high-value crop production and social assets including access to land and credit. Alternately, Hoang (2006) uses differences in social influence as a metric of equity within a smallholder community. Social influence is determined through social networks analysis. Equity can also be expressed qualitatively through participatory wealth ranking exercises (Kisoza, 2014).

Several authors define a special category of food equity: the availability of food to those who need it (Altieri, 1999; Loos et al., 2014). Metrics appropriate to food equity can be found under "Food security."

Additionally, the impacts of an SI effort on equity can be assessed. Giller (2011) characterizes this kind of equity as “uptake and benefits among better off and poorer” farmers. Several projects have explicitly measured uptake and benefits among male and female farmers (see “Gender equity”). However, we have not identified additional, explicit metrics of project impacts on equity.

Erosion (strong metrics)

Soil erosion is a major problem in smallholder systems, particularly in areas where smallholders are forced to farm sloped land (Schmitt-Olabisi, 2012). Several metrics of erosion have been employed in the SI literature. Most metrics of erosion focus on the field or farm level, but metrics of erosion at the community level do exist.

The raw rate of erosion can be 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). The C-value is calculated based on the erosion experienced in a cropping system, compared with the erosion that would be experienced in the same environment under continuous tilled fallow. 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).

Erosion can also be measured based on farmers’ perceptions. The incidence of erosion can be expressed as the percent of farmers experiencing erosion (Schmitt-Olabisi, 2012). Farmers perceptions of the change in soil depth over the past 20 years can be elicited to assess the severity of erosion (Swinton, 2000). Furthermore, the intensity of erosion control undertaken by farmers can be measured as the percent of farmers who report employing erosion control technologies or the percent of total cropland on which erosion control technologies are implemented (Schmitt-Olabisi, 2012; Smith and Plucknett, 1995).

Tenge et al. (2006) present an in-depth, participatory metric of soil erosion at the community level. In participatory erosion mapping, a catchment map is drawn by a community assembly, and indicators of erosion are identified. Lead farmers then visit each field, rank its erosion status using the previously identified indicators, and estimate yield loss due to erosion. Estimates are validated by the community, and also validated against biophysical measurements taken by researchers.

Farmer knowledge integration (limited metrics)

Many commentators on SI propose that intensification technologies will be most socially and environmentally sustainable when they are fully integrated into farmers’ local knowledge systems (Doré et al., 2011; Pretty, 1997). Unfortunately, metrics of the degree to which SI efforts are integrated with farmers’ knowledge systems are very scarce. One metric is farmer-to-farmer information exchange, expressed as the percent of farmers who get information from other farmers (Kimaru-Muchai et al., 2013). Furthermore, we would propose that the involvement of farmers in selecting criteria by which to evaluate the intensification effort can serve as an implicit metric of the integration of SI with farmers’ knowledge systems (Snapp and Silim, 2002; Tenge et al., 2006).

Farmer participation (metrics lacking)

Farmer participation is a widely cited indicator of sustainability in intensification efforts targeting smallholders (Tittonell, 2014; Vanlauwe et al., 2014). In one of the foundational papers on SI, Pretty (1997) calls for “full participation of farmers and other rural community members in all processes of problem analysis, and technology development, adaptation and extension.” However, some commentators worry that as the field of SI has developed, the emphasis on farmer participation has been gradually lost (Loos et al., 2014). It is difficult to evaluate this claim, as we are not aware of any concrete metrics of meaningful farmer participation in SI initiatives.

Van de Fliert and Braun (2002) present a framework for farmer participation in agricultural development initiatives which may provide guidance for the development of metrics. Their framework focuses on the realms of research and development, extension, and impact evaluation. In research and development, project goals must be formulated by scientists working together with the community. This begins with problem analysis and prioritization of problems. Farmers must be involved in the evaluation of technology options based on their effectiveness and appropriateness to the local system. In some cases, farmers will also be involved in the selection of technologies to test. In extension, a training program should be developed by researchers in collabouration with farmers, and modified based on farmers' feedback. The extension program may be implemented by professional extensionists trained in participatory methodology, or it may be implemented by farmer facilitators. Internal monitoring must be carried out across all stages of the project, and farmers must be involved in planning and carrying out evaluation.

Farmer preference (adequate metrics)

Farmer preference for SI technologies is sometimes used as an indicator of whether those technologies are socially sustainable. A simple metric of farmer preference is the percent of farmers who state that they favor a particular technology or practice (Altieri, 1999; Snapp et al., 2010). These farmer preference data can be disaggregated by agroecological zone or other environmental factors, reflecting the appropriateness of the technology for farmers working in different environments (Snapp et al., 2002). Farmer preference can also be disaggregated by having farmers score crops or technologies in a number of categories, such as food security, cash income, input cost, etc. (Owenya et al., 2012; Rusinamhodzi et al., 2012).

An open-ended, qualitative metric of farmer preference involves eliciting farmers’ criteria for evaluating a technology (Maass et al., 2013; Snapp and Silim, 2002). Farmers’ criteria for evaluation can be obtained through open-ended surveys, in which farmers are asked to state positive or negative attributes of the technology. Farmers’ responses are then coded, and criteria for evaluation are presented in terms of the frequency with which they are expressed.

Fodder production (adequate metrics)

In grazing systems and integrated crop / livestock systems, the capacity to produce fodder on the farm is an important SI indicator (Garrity et al., 2010; Klapwijk et al., 2014). When crop residues are gathered and transported to penned animals for use as fodder, fodder production can be measured as T biomass produced / ha (Boval et al., 2014). In grazing systems, fodder production is contingent on the condition of the rangeland. Range condition can be assessed by researchers as the primary production of rangeland plant communities (Lusigi, 1995). Herders can assess change in rangeland condition by comparing present-day condition to the condition in previous years (Klintenberg et al., 2006). Photos taken of the same location in subsequent years can aid in this assessment.

Fodder quality (adequate metrics)

The quality of fodder produced on the farm is another important SI indicator in livestock systems. Fodder quality can be measured in terms of the presence of toxins in fodder, particularly aflatoxin and other mycotoxins (Bekunda, 2012). In rangeland systems, fodder quality can be assessed as the nutrient intake of grazing animals (Lusigi, 1995). This is calculated based on the proportion of different rangeland plants in the animals’ diet, and the nutrient contents of each plant. The presence of legumes in the animal’s feed or forage can also be used as a rough metric of fodder quality (Powell et al., 2004).

Food safety (limited metrics)

Food safety is not among the most common indicators used in the evaluation of SI efforts, but some investigators have raised it as a priority (McDermott et al., 2010). One area of food safety concern is the presence of aflatoxin and other mycotoxins in grains and dairy products. Aflatoxin contamination in food products can be measured relative to a critical threshold of 20 ppm beyond which foodstuffs could be dangerous to human health (Bekunda, 2012). Another area of food safety concern is the presence of pesticide residues on produce. Health risk from pesticide residues can be measured based on the environmental impact quotient (EIQ) of the pesticide program used in vegetable production (Schreinemachers et al., 2011). This is calculated using a standard EIQ scores assigned to agrochemicals based on their potential to impact human and environmental health, along with the rate and frequency of pesticide application and the concentration of each active ingredient in the mixtures applied.

Food security (adequate metrics)

Food security is a critical objective of SI efforts in smallholder systems (Godfray and Garnett, 2014; ISPC, 2014). Broadly, food security denotes the availability of food to those who need it (Altieri, 1999). Household-level food security can be measured directly as the months of available grain stores reported by farmers (Lewis et al., 2011). Its inverse, food insecurity, can be measured as the percent of farmers who report reducing food consumption due to lack of food during the hungry season. Finally, food security improvements at the household level due to adoption of an SI technology can be measured as the number of days of additional food that the intervention provided to the average household (Garrity et al., 2010). Several additional metrics relevant to food security are presented under “Nutrition.”

Food self-sufficiency (adequate metrics)

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 calories required (Kamanga et al., 2010). Similar analyses have been conducted using 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, whereas production of foodstuffs can be measured directly by researchers (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).

Gender equity (limited metrics)

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. Assessments of gender equity are not common, however. Given the emphasis placed on this indicator, we believe there may be a need to further develop and standardize metrics of gender equity.

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). See the “Equity” section for a description of this index. Gender equity in a given SI effort can 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 labour, or the proportion of SI-related work performed by men relative to that performed by women (Powell et al., 2004).

Greenhouse gas emissions (adequate metrics, contention)

There is strong emphasis on climate change mitigation within the SI literature, and as such, greenhouse gas (GHG) emissions are an essential SI indicator (Godfray and Garnett, 2014; ISPC, 2014). Calculation of GHG emissions requires accounting of all inputs and outputs of carbon within an agricultural system (Rosenzweig and Tubiello, 2007). Empirical determination of GHG emissions is therefore highly data intensive. A more feasible approach, particularly in data-sparse environments such as smallholder farming systems, is to use crop simulation models to estimate GHG emissions (Bellarby et al., 2014).

There are two principal metrics employed for GHG emissions from agricultural systems. The first, emissions per unit of production, is expressed in T CO_2 / kg grain yield in crop systems (Bellarby et al., 2014), or T CO_2 / kg milk or meat yield in livestock systems (Tarawali et al., 2011). For GHGs other than CO_2, a CO_2 equivalence value is employed. An alternative is to measure GHG emissions in terms of the emissions per unit of resources used. In crop systems this is measured per unit land, expressed in T CO_2 (or equivalents) / ha (Bellarby et al., 2014).

To a certain degree, these two metrics reflect divergent perspectives on the meaning of sustainability, and have therefore been a subject of debate in the literature (Struik et al., 2014). One group of authors equate sustainability with maximizing the efficiency and minimizing the environmental impact of food production (Keating et al., 2010). Others focus on ecological thresholds, asserting that there are certain limits that must not be exceeded (Walker et al., 2010). Measurement GHG emissions as a function of food produced reflects the efficiency perspective, whereas measuring absolute GHG emissions per unit land reflects the ecological thresholds perspective.

Additionally, some studies of SI systems focus on the emissions of a single GHG other than CO_2. In livestock systems, T CH_4 produced / kg feed digested is used as a metric of methane production by cattle (Tarawali et al., 2011). Similarly, NH_4 emissions are directly measured where N volatilization is a particular concern (Klapwijk et al., 2014).

Household purchases (limited metrics)

One occasionally proposed SI indicator is the increase in total household purchases among participants in an SI effort. This can be measured quantitatively as the percent change in household consumption over a given span of time (ISPC, 2014), or qualitatively based on farmers' reports of whether their purchase of household goods has increased (Owenya et al., 2012).

Information access (adequate metrics)

Farmers' access to information about agriculture is frequently cited as a sustainability indicator (Rai et al., 2011; Tilman et al., 2002). Information access can be measured in terms of access to information in general, or in terms of knowledge about a specific SI technology or practice. One metric of farmers' access to information is their level of connectivity within the agricultural knowledge network (Hoang et al., 2006). The social network analysis required to obtain this metric is somewhat data intensive, but it has the advantage of measuring farmers' level of involvement in all forms of information exchange. Access to information about agriculture can also be scored by farmers, and this scoring exercise can involve multiple categories including agricultural extensionists and other 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 that they could teach the practice 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).

Input access (limited metrics)

The availability of agricultural inputs such as fertilizers and water is occasionally proposed as an indicator of sustainability in SI interventions that rely upon inputs. Graciana (2006) measures access to water as the percent of farmers in the study area reporting either formal access to water (i.e. an irrigation permit) or informal access to irrigation water. Input access can also be estimated based on farmers' use of the input. Fungo et al. (2013) measure fertilizer access as the percent of farmers reporting use of fertilizer.

Input efficiency (strong metrics)

Maximizing the efficiency of input use 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). Partial factor productivity can also be measured as kg grain yield / total kg of nutrients applied. In livestock systems, partial factor productivity can be measured as kg animal product yield / kg dry feed intake (Tarawali et al., 2011). A variant on partial factor productivity has been proposed to measure the efficiency of intercrops relative to monocrops (Valet and Ozier-Lafontaine, 2014). The efficiency equivalent ratio expresses the total inputs applied to an intercrop across a given area / the total inputs applied to the monocropped areas necessary to obtain equivalent yields of each constituent crop.

An alternative metric of input efficiency is the eco-efficiency score. In the eco-efficiency framework, the performance of each individual cropping system is contrasted with an eco-efficiency frontier, representing the optimally efficient use of all inputs (Keating et al., 2010). All inputs and outputs must be fully monetized in order to employ this metric. The eco-efficiency frontier can be determined using data on inputs and outputs for a range of cropping systems representative of the region. Linear programming models are then used to identify the existing frontier of optimal net resource use (Gadanakis et al., 2015). Each farming system is assigned an eco-efficiency score based on its proximity to the eco-efficiency frontier. A close relative of eco-efficiency, energy efficiency analysis, contrasts farming systems based on the ratio of total system outputs (in kg grain or Mj energy) to the total system inputs in Mj (Tyedmers and Pelletier, 2006).

Input intensity (adequate metrics)

The intensity of input use (i.e. the quantity of inputs used per unit area) is sometimes used as an indicator of intensification in SI systems. One metric of input intensity is energy intensity, expressed in Mj / ha (Giller et al., 1997; Tyedmers and Pelletier, 2006). This metric is based on fossil fuel inputs to the system. Alternately, input intensity can be expressed in economic terms as $ value of inputs applied / ha (Shriar, 2000). Finally, the rate of chemical fertilizer application can serve as a metric of overall input intensity, expressed as kg fertilizer applied / ha (Tittonell et al., 2007).

Internal nutrient cycling (strong metrics)

When nutrients are cycled within an agroecosystem, farmers gain access to fertility that would otherwise come from purchased inputs. Therefore, the degree of nutrient cycling in an agricultural system is frequently cited as an indicator of environmental sustainability and productivity in SI systems (Garrity et al., 2010; Vanlauwe et al., 2014). The most simple metric of internal cycling is the use of farm-generated biological inputs such as manure and compost (Powell et al., 2004; Pretty et al., 2011). In agroforestry systems, the cycling of leaf litter can be used as a metric of internal nutrient cycling (Asase et al., 2008; Demessie et al., 2015). Leaf litter cycling is determined based on the quantity of leaf litter produced, and its rate of decomposition in the litter layer.

Other metrics of internal cycling deal with specific nutrients. The rate of N mineralization in the soil can be used as a metric of internal nutrient cycling (Clermont-Dauphin et al., 2014). A related metric is the mineralizable N in the soil (Myaka et al., 2006). Both these metrics measure the release of nutrients from biological forms, and thus are likely to reflect internal cycling of nutrients. It should be noted, however, that manure is sometimes purchased from other farms, and livestock may be allowed to graze on neighboring fields. Therefore, metrics such as N mineraliztion might not always reflect the cycling of nutrients within the farm.

Finally, some metrics of internal cycling capture multiple stocks and flows of nutrients across the agricultural system. 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. When researchers quantify these stocks and flows with regard to a specific nutrient such as N, a cycling index for N can be computed, which measures the degree of internal cycling present in the system (Rufino et al., 2009).

Irrigation (adequate metrics)

Some authors employ farmers' use of irrigation as a metric of SI. The rate of irrigation at the community level can be measured as the percentage of farmers who report irrigating their crops (Graciana, 2006). At the field level, the intensity of irrigation can be measured as mm of irrigation water applied (Wani et al., 2003).

Labour intensity (adequate metrics)

Labour intensity is occasionally used as an indicator of intensification in SI systems. Labour intensity can be measured as person time / ha (Schreinemachers et al., 2011; Zimmerer, 2013). While labour intensity can be used as a metric of intensification, it can also be a negative indicator of the economic and social sustainability of a system. Labour is typically included as a cost in benefit / cost analysis (Kamanga et al., 2014) and farmers often cite labour savings (i.e. reduced labour intensity) among positive attributes of cropping systems (Owenya et al., 2012; Snapp and Silim, 2002).

Labour productivity (adequate metrics)

Labour is a resource that is available to smallholder farmers who might otherwise be very resource limited. Therefore, labour productivity is widely proposed and widely measured as an SI indicator (Struik et al., 2014; The Montpelier Panel, 2013). The metric generally used for labour productivity is returns to labour, most frequently calculated as the $ crop value / person day of labour (Silici, 2010; Twomlow et al., 2006). Returns to labour can also be calculated as kg crop produced / person day (Tittonell et al., 2007). Labour is also among the inputs considered in eco-efficiency analysis and benefit / cost analysis, and therefore labour productivity is one component of both these metrics (Kamanga et al., 2014; Keating et al., 2010). See "Input efficiency" for more details on eco-efficiency analysis, and the "Crop value" for more details on benefit / cost analysis.

Labour reduction (limited metrics)

Commentators who view overall quality of life for smallholder farmers as one of the objectives of SI sometimes propose labour reduction as a metric of human welfare in SI systems. Labour reduction in agriculture can allow farmers more time to engage in non-agricultural income generating activities, increasing their overall access to resources (Altieri, 1999; Owenya et al., 2012). It is worth noting that labour reduction and labour productivity, while sometimes conflated, are separate things. For example, technologies which increase labour productivity may also incur increased expenses. In such a scenario, the farm's total output may increase while the amount of labour required of the farmers remains the same.

Labour reduction can be measured as reduction in the total time required to perform agricultural activities (Owenya et al., 2012). These data are obtained through detailed labour budgets kept by farmers, and disaggregated by activity. Reports from farmers of reduced labour requirements, obtained in open-ended surveys or focus groups in which farmers evaluate SI technologies, can also be used as a metric of labour reduction (Snapp and Silim, 2002).

Market access (limited metrics; contention)

Market access is frequently cited as in indicator of economic sustainability in SI systems. While some commentators cite market access alone as an adequate indicator (The Montpelier Panel, 2013; Vanlauwe et al., 2014), others assert that smallholders will only benefit from access to markets in which they have bargaining power (McDermott et al., 2010) or in which they possess a comparative advantage (Rai et al., 2011). Farmers' physical access to markets can be measured as the distance to the nearest market (Clay et al., 1998; Owenya et al., 2012). However, we have not identified metrics of market access in the SI literature that account for farmers' bargaining power or comparative advantage.

Nutrient balance (adequate metrics; contention)

The nutrient balance of an agroecosystem refers to the net balance of nutrient inflows and nutrient outflows. A positive nutrient balance implies an accumulation of nutrients within the system, while a negative balance implies mining of the soil for nutrients (Scoones and Toulmin, 1998). Several authors have therefore proposed the nutrient balance as an indicator of ecological and productive sustainability in SI systems. In its most simple form, the nutrient balance can be calculated as the total nutrients applied in fertilizer, minus the total nutrients exported in grain (Mtengeti et al., 2015). However, this approach does not account for other forms of nutrient export such as volatilization or leeching. Empirical determination of a more complete nutrient balance would be very data intensive. In data-sparse environments, simulation models can be used to estimate the N balance in smallholder systems in a manner that accounts for all major inflows and outflows (Tittonell 2007).

Nutrient budgets do not always present a comprehensive picture of resource flows in agricultural systems. Scoones and Toulmin (1998) point out that in systems which incorporate grazing, nutrient budgets may actually disguise the mining of nutrients from rangeland areas or other farmers' fields. Also, nutrient budgets conducted at a single point in time may not reflect resource flows at other points in the season or in other years. Tittonell et al. (2007) made efforts to correct this deficiency by basing their N budgets on participatory resource mapping with farmers. However, Powell et al. (2004) point out that budgets for a single nutrient may not adequately reflect the balance of all nutrients in crop / livestock systems, as the N/P ratio of manure tends to differ from the relative N and P requirements of crops.

Nutrient export (limited metrics)

Nutrient export through the volitilization of N, leeching of N and P, or loss of nutrients through erosion are major causes of environmental impact in agroecosystems (Tilman et al., 2002). While several commentators on SI have proposed nutrient export as relevant indicator of sustainability (Carsan et al., 2014; Rai et al., 2011), nutrient export rarely measured in smallholder systems. Nutrient export has been measured in crop-livestock systems as N taken off the field for use as fodder or consumed by grazing animals (Powell et al., 2004; Tittonell et al., 2007). Nutrient export has also been measured in terms of NH_4 volatilization and NO_3 leeching (Klapwijk et al., 2014). Environmental damage from nutrient export may not be a major concern where rates of input use are low. However, the continuing intensification of smallholder agriculture may warrant increased attention to nutrient export.

Nutrition (adequate metrics)

Nutrition is frequently cited as an indicator of human wellbeing in SI systems. Nutrition is most frequently measured at the community scale, and at this scale refers to the "spectrum and adequacy of foods available to communities" (Garnett et al., 2013). Nutrition can be measured using rates of child stunting (Bezner Kerr et al., 2011; Remans et al., 2013). This is reflected in the mean weight-for-age or height-for-age Z scores of children under three years old. Community-level nutrient deficits can also be calculated based on the aggregate nutrient demand of the community (calculated from standard conversion tables) versus the aggregate nutrient consumption (obtained from surveys of food consumption) (Remans et al., 2013). Additionally, nutrition can be measured based on farmer reports of access to a healthy diet (Owenya et al., 2012).

Nutrition can also be measured at the household scale. (Silici, 2010) measured household nutrition using a food consumption score, based on farmer-reported consumption of foodstuffs, and weights assigned to those foodstuffs based on their nutrient content.

Perennial cover (adequate metrics)

Perennial plants in agricultural systems can aid in the cycling of nutrients, retention of soils, and sequestration of carbon (Garrity et al., 2010; Minang et al., 2012). Therefore, perennial cover is sometimes used as a metric of environmental sustainability in SI systems, particularly those related to agroforestry. Perennial cover is measured either at the scale of the farm, or at the scale of the local landscape (i.e. the community scale). Perennial vegetation at the farm scale can be measured as the percent tree cover (ISPC, 2014) or the number of trees / ha (Garrity et al., 2010). Perennial cover can also be measured as the percent cover at both the tree and bush levels (Holt-Giménez, 2002). Other authors working in SI systems point to the presence of perennially vegetated buffer zones as an indicator of sustainability, but precise metrics are not given (Vanlauwe et al., 2014).

Perennial cover at the local landscape scale can be measured in terms of the proportion of perennially vegetated areas (forest, bush fallow) within a given radius surrounding the cultivated field (Ndemah et al., 2003). Also, the rate of deforestation has been used to measure changes in perennial vegetation at the local landscape scale (Steiner et al., 2000).

Pest pressure (adequate metrics)

Sustainable intensification efforts aim to increase productivity in agriculture, which can often be accomplished by reducing pressure from pests (including insects, weeds and disease-causing organisms). Therefore, many SI theorists have pointed to pest pressure as a key indicator of both productivity and sustainability in SI systems (Garrity et al., 2010; Giller et al., 2011). Pest pressure is generally measured at the field level.

Different metrics of pest pressure are used depending on the type of pest under consideration. Aboveground insect pests can be measured as the percent of crop plants damaged (Khan et al., 2008) or the number of pest organisms present per plant (Ndemah et al., 2003). For soil-living insect pests, pressure can be determined based on the number of soil-living pests obtained per sample (Clermont-Dauphin et al., 2014). Relative weed pressure can be measured using a weed infestation score (Tittonell et al., 2007). Finally, disease pressure can be measured based on the number of plants or panicles that show signs of infestation (Giller et al., 2011; Zhu et al., 2000).

Pest pressure can also be measured relative to a specific intervention. One metric is the number of pest species negatively affected by the intervention (Ratnadass and Barzman, 2014). Farmer reports of reduced pest pressure due to an intervention are also used as a metric (Snapp and Silim, 2002).

Quality of life (limited metrics)

Quality of life is sometimes presented as an indicator of human wellbeing and social sustainability in SI systems. However, quality of life is rarely measured directly. A farmer-reported metric of changes in quality of life is presented by Morse (2002). Farmers are asked about general quality of life and family health both now and in the past. The metric is presented as the percent of farmers reporting positive, negative, or no change in quality of life or health. In other survey efforts, farmers have been asked about factors related to quality of life such as time for social activities and ability to provide hospitality to guests (Owenya et al., 2012).

Resilience (limited metrics)

The resilience of agricultural systems, or their ability to recover from disturbances, is frequently proposed as a sustainability indicator in SI systems (Doré et al., 2011; Walker et al., 2010). Resilience can function at multiple scales, and it is associated with the concept of ecological thresholds. In this sense, resilience implies the capacity to maintain or quickly recover a given level of productivity in the face of disturbance, rather than being jolted into an alternate, less productive stable state (Walker et al., 2010). Resilience does not necessarily mean that an agroecosystem remains exactly the same (Struik et al., 2014). Instead, resilience can imply adaptive change to meet the demands of changing conditions. See “adaptive capacity” for related metrics.

Béné (2013) proposes a metric of resilience at the community level based on the costs of recovery from disastrous events. The costs of preparing for a possible event, the direct impact of the event, and the costs of recovery from the event must all be accounted for. Costs cover more than simply financial losses – they also include environmental, social, psychological, and food security costs. Béné does not propose a method for quantifying all of these costs, but the framework appears useful for evaluation of SI efforts.

Giller (1997) proposes that the resilience of agroecosystem function be measured in terms of the redundancy of organisms in each functional group within the ecosystem. Therefore, even if some organisms are lost, the basic function of the system is retained.

Holt-Gimenez et al. (2002) made an extensive effort to measure improvements in resilience due to the use of SI practices among smallholders. Shortly after a major hurricane, surveys were performed on smallholder farms using agroecological practices, as well as other smallholders using conventional practices on nearby fields with similar soil and slope. Damage from the hurricane was compared based on the area and severity of soil erosion, and the estimated loss of crop value. This study was interesting in that field data were collected by hundreds of farmers who got training in research methods. Owenya (2012) employs a simpler metric, eliciting farmers views on challenges they have faced and how their responses to those challenges have changed since taking part in an SI effort.

Resource conflict (limited metrics)

Conflict over resources is occasionally cited as an indicator of the social sustainability of intensification efforts, generally in livestock-based systems. Kisoza (2014) presents a metric of resource conflict based on farmers' perception of conflict in and between herding communities. Participatory rural appraisal approaches were used in a number of villages to identify conflicts over resources. Participants then ranked conflicts on a scale of intensity, and described the parties to the conflict. Based on this information, the conflict intensity in each village and the principal parties to the conflict were determined. Farmers were also interviewed about the perceived sources of the conflict and how it could be resolved. These data were used to recommend pathways toward conflict resolution.

Risk (adequate metrics)

Risk is frequently cited as an important indicator of sustainability in SI systems (Godfray and Garnett, 2014; Rai et al., 2011). 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 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). Keating presents an approach for visualizing economic production risk, in which cropping systems are plotted with their mean return on the y axis, and the standard deviation in returns (representing economic risk) on the Y axis. This allows straightforward assessment of the relative risks and benefits of a range of systems.

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. Questions were open ended, allowing respondents to identify risks of any kind. For each risk, respondents were asked to describe how they coped with this issue in the past, and factors that make it difficult to cope with in the present. This information was used to score the breadth and severity of perceived risks in a community. Risks were then mapped on axes of incidence and severity. The resulting scatterplot was presented as a community risk map.

Seed / stock access (limited metrics)

Access to improved seed can be an important factor in SI efforts which involve the use of new crop varieties (Giller et al., 2011). Seed access can be measured as the percent of farmers reporting difficulty obtaining seed of a particular crop or variety (Snapp and Silim, 2002). Alternately, access constraints across a variety of crops can be assessed in a focus group setting (Mhango et al., 2013). The availability of improved livestock genetic resources has also been cited as constraint to intensification in livestock-based systems (McDermott et al., 2010). However, we were unable to locate metrics of access to improved livestock in the SI literature.

Social capital (adequate metrics)

Social capital, which refers to the value of human relationships, is often cited as an indicator of social sustainability in the SI literature (ISPC, 2014; Pretty et al., 2011). Metrics of social capital can focus on the level of the household, or can span household and community scales. At the household level, Swinton (2000) assesses social capital using an index of personal connections and membership in formal organizations. In this metric, social capital is determined based on how many people a household associates with regularly, their membership in formal organizations, and participation in collective land management schemes. Alternately, Silici (2010) presents an index of social capital at the community level. Ten variables relating to social capital are identified, four of which relate to membership in formal organizations such as farmers' groups, and six of which relate to trust and reciprocity in personal relations. Bayesian network analysis is used to determine the relation of these variables to SI practices.

Hoang (2006) employs social network connectivity and structure as metrics of social capital among smallholder farmers. In this example of social network analysis, important networks in the community are identified based on conversations with farmers. Households' level of connectivity the identified networks (kinship, conversation, and advice) is then quantified based on the number of links that each household possesses to other households. Connectivity at the household level provides information about varying access to social capital among households. Additionally, examination of the full social network provides insight about the strength and structure of social relations within the community.

Soil biological activity (strong metrics)

Several commentators on SI propose soil biological activity as an indicator of ecosystem function in SI systems (Garrity et al., 2010; Rai et al., 2011). Soil biological activity is closely related to internal nutrient cycling and soil quality, which are presented as separate indicators in this review.

Soil biological activity can be measured in a general sense as the total microbial biomass in the soil (Bommarco et al., 2013; Clermont-Dauphin et al., 2014). Net biological activity in the soil can also be measured as the soil respiration rate (Clermont-Dauphin et al., 2014). Other metrics of biological activity deal with specific soil processes. 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). Decomposition rate can be determined based on the loss of mass from litter samples contained in a permeable bag. 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 that occurs in the soil, particularly in association with legumes and other N fixing plants. The percentage of legume N derived from the atmosphere is one metric of N fixation (Oikeh et al., 2012; Ojiem et al., 2007). When legume biomass production is known, along with its atmosphere-derived N content, it is possible to calculate N fixation at the field level. N fixation can also be measured indirectly as the count or dry weight of N fixing nodules per legume plant (Oikeh et al., 2012).

Soil cover (adequate metrics)

The amount and duration of vegetative cover on the soil affects its ability to resist erosion, retain water and cycle nutrients. Therefore, soil cover is frequently cited as an indicator of environmental sustainability in SI systems (Garrity et al., 2010; The Montpelier Panel, 2013). Soil cover can be measured at a given point in time as the percent bare ground (Lusigi 1995), or percent vegetative cover at ground level, bush level, and canopy level (Holt-Giménez, 2002). Soil cover can also be measured across time as the proportion of the year in which plants are present on the field (Snapp et al., 2010).

Soil quality (strong metrics)

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, but this capacity has many dimensions (Clermont-Dauphin et al., 2014; Rai et al., 2011). Metrics of soil quality fall into four general categories: physical properties, chemical properties, biological properties and indices of soil quality which are comprised of multiple simple metrics. Metrics of soil quality are generally relevant within the root zone of crop plants, which varies based on the soil and cropping system.

One of the most commonly employed physical 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). Total soil carbon is also sometimes used as a metric of soil quality (Lewis et al., 2011; Mulumba, 2015). Soil C and organic matter influence the capacity of the soil to retain nutrients and water, as well as multiple other properties. 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 the water efficiency of the cropping system. The water holding capacity of soils (i.e. field capacity) can also be used as a metric (Tittonell, 2014). Soil compaction is a physical metric affecting both water infiltration and the ability of roots to penetrate the soil (Steiner et al., 2000). Depth of the topsoil is another simple, physical metric used to assess soil quality (Holt-Giménez, 2002). Soil aggregate stability, which is related to the soil's capacity to resist erosion, can also be employed as a metric of soil quality in agroecosystems (Clermont-Dauphin et al., 2014).

Chemical properties employed as metrics of soil quality consist of the abundance of specific nutrients, and the overall nutrient holding capacity of the soil. Several metrics of soil N are used. In some cases total soil N is used as a soil quality metric (Demessie et al., 2015; Gelaw et al., 2015), while in other cases only mineral N and mineralizable N are measured (Myaka et al., 2006). Other nutrients commonly measured in the assessment of soil quality include extractable P, and total Ca, Mg and K (Mhango et al., 2013; Tittonell et al., 2007). The most common metric of nutrient holding capacity is the cation exchange capacity (Mhango et al., 2013; Tittonell et al., 2007). Soil pH is also frequently measured in the assessment of soil quality.

Metrics of soil biological properties relevant to soil quality are covered under "soil biological activity."

Several indices of soil quality, each consisting of a number of simple metrics, are employed in the SI literature. Silici (2010) presents the Soil Fertility Index (SFI), a relatively straightforward index for comparing soil quality between two fields. The SFI is computed as ($P_{Intervention}/P_{Control} + K_{Int}/K_{Ctl} + Ca_{Int}/Ca_{Ctl} + Mg_{Int}/Mg_{Ctl}$). McCune (2011) employs a soil quality index consisting of soil organic matter, aggregate stability, water permeability, upper and lower limits of plasticity, the portion of clays bound in organic-mineral complexes, and pH. Cluster analysis is used to group farms by soil fertility based on these criteria.

Stocking rate (adequate metrics)

In livestock grazing systems, the stocking rate is sometimes employed as a metric of intensification in SI efforts. Stocking rate can be measured as T live weight / ha (Boval et al., 2014), or as the number of animals / ha (Lusigi, 1995). The stocking rate relative to the carrying capacity of the range is also a relevant indicator of sustainability (see "carrying capacity") (Lusigi, 1995).

Water efficiency (strong metrics)

Water use efficiency is frequently employed as a metric of sustainability and productivity in agricultural intensification efforts, particularly in rainfed smallholder systems (Garrity et al., 2010; The Montpelier Panel, 2013). Water use efficiency can be based on the total water input to the agricultural system, or based only on the water involved in evapotranspiration (ET). Water use efficiency at the field scale with regard to total water input in rainfed agroecosystems is measured as grain yield / mm rainfall (Anderson et al., 2006; Chikowo et al., 2015). In irrigated systems, the water application efficiency at the field scale can be measured as the increase in crop yield due to irrigation / m^3 irrigation water applied per hectare (Wani et al., 2003).

At the farm scale, water use efficiency can be measured as kg agricultural products / m^3 water entering the agroecosystem (Kahinda and Masiyandima, 2014). This metric is appropriate for rainfed or irrigated systems.

Efficiency of ET water use can be measured as yield / mm ET, where ET is total precipitation minus losses to runoff and deep drainage (Anderson et al., 2006). This metric is appropriate for separating the efficiency of water used by vegetation from other water sinks. In integrated crop / livestock systems, efficiency of ET water at the farm scale can be measured as the $ value of animal products produced (including meat and milk) / m^3 total ET from land used to grown feed crops during the growing season (Descheemaeker et al., 2011).

Finally, the relative water use efficiency of an intercrop compared with a corresponding monocrops can be measured as m^3 water used by an intercrop / m^3 used by the area of constituent monocrops necessary to produce an equivalent yield.

Water quality (limited metrics)

Water quality is proposed by some authors as an indicator of human wellbeing in SI systems (Herrero et al., 2010; Tilman et al., 2002). Water quality can be of particular concern in animal agriculture, where animal waste may contaminate sources of drinking water. One indicator of water quality employed in the SI literature is the bacterial count of a body of water (Lusigi, 1995). NO_3 concentrations in water are another important indicator of water quality in agricultural systems (Klapwijk et al., 2014). Despite the importance of water quality for human health, we have not found other metrics of water quality used in the evaluation of smallholder SI systems.

Ways of life (metrics lacking)

Several agricultural development theorists propose that the capacity for communities to maintain cultural autonomy and traditional ways of life throughout the process of intensification is an important indicator of social sustainability (Bosshard, 2000; Lusigi, 1995). However, we have not been able to locate any metrics related to this indicator in the SI literature.

Yield (strong metrics)

Yield is by far the most common indicator used in the SI literature. In cropping systems, yield refers to the production of crops per unit land area. This can be measured either in kg grain / ha (ISPC, 2014; Rai et al., 2011) or as $ crop value produced / ha (Kamanga et al., 2014; Zhu et al., 2000). In livestock systems, yield can also be 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 grain (Herrero et al., 2010).

One variant on yield is the land equivalent ratio (LER) (Altieri, 1999; Valet and Ozier-Lafontaine, 2014). The LER is typically used to measure the yield of intercrop systems relative to monocrops. For an intercrop containing two crops (A and B) the LER would be calculated as (yield of A in intercrop / yield of A in sole crop) + (yield of B in intercrop / yield of B in sole crop). Thus, an LER greater than 1 indicates that the intercrop is more productive than either constituent monocrop.

Yield gap (adequate metrics)

Some SI researchers employ the yield gap as an indicator of intensification at the field scale (Bommarco et al., 2013). Authors typically employ the attainable yield gap, or the difference between the actual yield of the cropping system and the attainable yield. 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. Yield gap analysis requires an estimate of the attainable yield, which can be obtained using several approaches. In the eco-efficiency framework, the attainable yield is indicated by the efficiency frontier (Keating et al., 2010; see "capital productivity"). The attainable yield can also be determined by simulating crop growth using a crop / soil / atmosphere model parameterized with local soil and historical climate data (Wani et al., 2003).

Yield variability (adequate metrics)

Yield variability can be employed as an indicator of economic and productive sustainability in SI systems. While yield variability shares many similarities with risk and resilience, it is distinguished by its concrete, quantitative definition. Yield variability is measured using the coefficient of variation (CV): the standard deviation in the yield / the mean yield (Morse et al., 2002; Rosenzweig and Tubiello, 2007). The CV can be computed using yields from many occurrences of a cropping system distributed in space, or based on yields from a single field in which a cropping system is grown for many subsequent seasons.

Metrics of system-level properties

Intensification (limited metrics)

In the context of SI, intensification is generally defined either as increased yield (Godfray and Garnett, 2014), or as increased input efficiency – i.e. "more output per unit input" (The Montpelier Panel, 2013). When the former perspective is taken, yield can be used as a straightforward metric of intensification. For those taking the latter perspective, the measurement of intensification is not always straightforward. For example, higher yields (more production / unit land area) are sometimes achieved by applying excessive inputs, therefore reducing input efficiency (Tilman et al., 2002). In order to be able to deal with such cases, a more nuanced metric of intensification is required.

Eco-efficiency is a general framework for measuring the intensification of agricultural systems (Gadanakis et al., 2015; Keating et al., 2010). In this framework, the performance of individual cropping systems is contrasted with an eco-efficiency frontier, representing the optimally efficient use of all inputs. This frontier can be identified by quantifying all inputs and outputs in monetary terms for a range of cropping systems representative of the region. Based on these data, linear programming models can be used to identify the existing frontier of optimal net resource use (Gadanakis et al., 2015). Each farming system can then be assigned an eco-efficiency score based on their proximity to the eco-efficiency frontier. While this framework is comprehensive, the use of monetary values for inputs and products has been criticized due to the tendency of input and output prices to fluctuate (ISPC, 2014; Shriar, 2000).

Shirar (2000) present an alternate metric for intensification, designed specifically for smallholder systems in which data on inputs and outputs are sparse. Farmers are surveyed about the full set of farming practices that they use, including chemical inputs, cultivation practices, livestock grazing, and so on. An intensity score is assigned to each practice. For chemical inputs this intensity score would be based on the $ value of chemicals used / ha, and for grazing systems it would be based on the stocking rate. Each practice is then weighted by researchers based on its contribution to food security. The overall intensification score for the farm is computed as the sum of the intensity scores of individual practices times their corresponding weights. Clearly, the development of an appropriate and research-based weighting scheme is critical to the effectiveness of this approach.

Multifunctionality (limited metrics)

The multifunctionality of agroecosystems, or their ability to provide multiple goods and services simultaneously, is frequently cited as an important indicator of sustainability in SI systems (Doré et al., 2011; Garrity et al., 2010). Since multifunctionality implies multiple processes working in synergy to produce multiple effects, metrics of multifunctionality must draw on several simple metrics of discreet phenomena. A number frameworks for measuring sustainability based on numerous simple metrics have been proposed and employed in the SI literature. These frameworks can also serve as metrics of multifunctionality (see "sustainability").

Sustainability (limited metrics)

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 working in the field of SI have proposed frameworks for measuring sustainability in smallholder systems. These frameworks consist of numerous metrics individual metrics of properties related to sustainability. The individual metrics appropriate for use in any given system depend on the ecological setting, social context, and priorities of the farmers involved (Steiner et al., 2000).

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 properties with associated metrics which are selected to represent different domains of sustainability. Steiner (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 properties (McCune et al., 2011), or biophysical and economic properties (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 (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.

Tradeoffs (adequate metrics; contention)

The SI literature is replete with discussions of tradeoffs between various aspects of sustainability and intensification. Some of these specific tradeoffs are presented in the "tradeoffs" section of this report. Here, we will focus exclusively on the measurement of tradeoffs. Tradeoff relationships can range from substitutive to complementary (Tittonell, 2013). The degree of complementarity between the factors involved in the tradeoff is referred to as the elasticity of competition between two objectives. To measure the elasticity of competition, one can plot the values achieved for objective A against the values achieved for objective B across a range of cropping systems (Tittonell, 2013). The shape of a curve fitted to these points (referred to as a tradeoff curve) will reflect the elasticity of competition. For example, if a large change in objective A corresponds with a relatively small change in objective B, this indicates complementarity. If a large change in objective A corresponds with a similarly large change in objective B, this indicates substitution. 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." As such, tradeoff curves can be employed to optimize farming practices such that tradeoffs are minimized.

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).

Gaps in the SI literature

Some indicators of sustainable intensification that are mentioned in the SI literature have few concrete metrics associated with them. We will briefly outline these areas of potential improvement in the SI literature.

Indicators of productivity

Productivity indicators are generally associated with strong collections of metrics. The only exception is the adaptive capacity of production systems. There are few existing metrics of adaptive capacity in the SI literature, and those that do exist focus on a limited range of simple adaptation measures (Rosenzweig and Tubiello, 2007).

Indicators of economic sustainability

Many indicators of economic sustainability in SI systems are associated with strong sets of metrics, but there are also some significant gaps in this domain. 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), and access to seed and livestock (Mhango et al., 2013; Snapp and Silim, 2002). It may be necessary to seek further metrics of farmers' access to resources in the agricultural economics literature, or develop new metrics appropriate to the SI context. The effects of SI efforts on household purchasing power are also rarely measured (ISPC, 2014; Owenya et al., 2012). Finally, metrics of market access to date have been restricted to the 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

Several indicators of human wellbeing in SI systems lack strong sets of metrics. In the SI literature to date, relatively little attention has been paid to food safety, and only a small number of metrics have been employed (Bekunda, 2012; Schreinemachers et al., 2011). As food safety concerns grow, it will likely be necessary to adopt additional 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 labour requirements due to SI efforts (Altieri, 1999; Owenya et al., 2012). Even fewer have measured the impacts of SI efforts on farmers' overall quality of life (Morse et al., 2002).

Indicators of environmental sustainability

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 concerned the carrying capacity of rangeland systems (Lusigi, 1995). Given the importance of ecological thresholds for environmental sustainability, it may be advisable to seek additional metrics in the ecology literature. Additionally, there are few metrics of nutrient export in the smallholder SI literature (Powell et al., 2004; Tittonell et al., 2007), though additional metrics could be sourced from the broader agroecology and environmental science literature.

Indicators of social sustainability

Indicators of social sustainability in SI systems are often associated with few or no concrete metrics in the SI literature. Social equity and empowerment represent one major gap in the 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). Further metrics of social equity and empowerment could likely be located in the rural sociology literature and adapted for use in SI systems.

There are also very few metrics in the SI literature having to do with social stability. We could only locate a single metric of resource conflict in the SI literature (Kisoza, 2014), though conflict is often a major concern in resource-limited situations. Also, while some SI authors discuss the importance of integrating SI efforts with traditional ways of life (Bosshard, 2000), no metrics of this integration could be found in the literature.

Animal welfare is a contested subject for which few metrics have been employed in the SI literature (Fraser, 2008). The single metric presented in this report represents a lowest common denominator, and would likely be viewed as inadequate by many concerned with animal welfare.

Finally, farmer participation and integration of SI efforts with farmers' knowledge systems represent a major gap in the literature on SI metrics. Attempts to measure the degree to which SI efforts are integrated with farmers' knowledge systems are rare (Kimaru-Muchai et al., 2013). Furthermore, we could find no concrete metrics of the degree of meaningful farmer participation in SI efforts. While some authors have presented frameworks for participatory research, these frameworks do not include clear criteria for evaluation (Van de Fliert and Braun, 2002). Given the fact that farmer participation is central to the SI concept (Pretty, 1997) and given critics' claims that meaningful participation has been sidelined in the SI agenda (Tittonell, 2014), it is essential that strong metrics of farmer participation be created or adopted from other fields of study.

Indicators spanning multiple domains

Several system-level properties which are often cited as SI indicators lack strong sets of metrics. Currently, there are only a few existing frameworks for measuring overall sustainability (Moore et al., 2014; Steiner et al., 2000), and overall intensification (Keating et al., 2010; Shriar, 2000). Measurement of sustainability and intensification will always depend on many metrics, but in order to bring those metrics together into a coherent picture, appropriate and clearly articulated frameworks are required. Likewise, resilience and multifunctionality in agroecosystems are frequently discussed in the SI literature but rarely measured (Garrity et al., 2010; Walker et al., 2010). The existing metrics of resilience each adopt a different perspective on resilience, ranging from purely ecological (Giller et al., 1997) to socioeconomic (Béné, 2013), to production-focused (Holt-Giménez, 2002). In order to appropriately assess this core property of sustainable agroecosystems, more metrics of resilience in multiple domains must be developed.

Conclusions

The sustainable intensification literature to date contains a rich array of indicators and metrics for evaluating SI efforts. Some gaps in the literature do exist, however, particularly in the domain of social sustainability. As these gaps are filled, we will increase our ability to measure multiple aspects of sustainable intensification from a variety of perspectives. It will remain the job 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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