Chapter 12
Assessing the Sustainability of Agricultural Technology Options for Poor Rural Farmers

Simone Kathrin Kriesemer, Detlef Virchow, and Katinka M. Weinberger

Abstract This chapter presents an analytic framework to identify agricultural innovations that are sustainable and suitable for the poorest and most vulnerable parts of the population. The framework contains a set of tools to collect and evaluate information on appropriate innovations based on relevant criteria. It considers the dimensions of environmental resilience, economic viability, and social sustainability, as well as technical sustainability considering important properties of the innovation itself. Information on already available agricultural innovations was collected in ten countries in South and Southeast Asia, as well as from the national and international agricultural research communities. A composite sustainability indicator was constructed to compare the collected innovations and radar charts were computed to visualize their performance in each sustainability criterion.

Keywords Poverty • Vulnerability • Sustainability indicator • Resilience • Innovation assessment

Background

Agriculture is a sector that urgently requires transformative changes to support sustainable development. This is true for several reasons. Firstly, the agricultural sector is important in respect to provision of food. As global population is expected to increase by two billion by 2050, and incomes rise, so will demand for more, more diverse and higher quality food. Secondly, farming also remains a key source of

---

S.K. Kriesemer (✉)
Horticulture Competence Centre, University of Bonn, Bonn, Germany
e-mail: sk.kriesemer@uni-bonn.de

D. Virchow
Center for Development Research (ZEF), University of Bonn, Bonn, Germany
e-mail: d.virchow@uni-bonn.de

K.M. Weinberger
Environment and Development Policy Section, United Nations Economic and Social Commission for Asia and the Pacific, Bangkok, Thailand
e-mail: weinbergerk@un.org

F.W. Gatzweiler, J. von Braun (eds.), *Technological and Institutional Innovations for Marginalized Smallholders in Agricultural Development*,
DOI 10.1007/978-3-319-25718-1_12

income – 75 % of the world's poor in developing countries live in rural areas, and in developing countries, the sector contributes 29 % of GDP and accounts for 65 % of all employment. And finally, agriculture uses resources that are becoming increasingly scarce – including land, soil, water, nutrients – and contributes to as well as suffers from the consequences of climate change (Godfray et al. 2010).

A transformation of the sector requires the adoption of new and innovative approaches that support sustainable outcomes. Many agricultural research organizations, both from the public as well as the private sector, and at national, regional and international levels, are involved in making solutions available for enhanced agricultural sustainability. Many of these have value beyond the particular local setting for which they were developed. However, decision takers at all levels, including farmers, extension workers and programme managers, require better tools to determine what innovations, i.e., what practices and technologies have relevance in certain settings. Traditional tools based on profit-maximization at the farm level, such as linear programming, do not take into consideration sustainability enhancing aspects and are therefore not sufficient in supporting the sustainability agenda.

The formulation of universal sustainable development goals that were agreed upon in the Rio+20 conference (UN 2012) is based on the principles of economic profitability, social justice and environmental friendliness: "Sustainable development is the management and conservation of the natural resource base and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such sustainable development (in the agriculture, forestry, and fisheries sectors) conserves land, water, plant and animal genetic resources, is environmentally non-degrading, technically appropriate, economically viable and socially acceptable". This definition was adopted in 1989 by FAO (1995).

A decision-making tool that aims for optimizing sustainability outcomes of the use of new technologies and innovations should, thus, take (at least) these three pillars of sustainable development into account. Yet, clearly, this is not an easy task. Sustainability does not have an intrinsic value unto itself, and different stakeholders and interest groups hold different assumptions about values, for instance, the relationship between economic development and human wellbeing, the relationship between present and future needs, the relationship between resource allocation and level of consumption, or views of what should be sustained. We therefore aim to present a tool that supports the decision-making process by making information on different aspects of sustainability available to decision-makers.

Evaluating Technologies for Sustainable Agriculture

The following paragraphs present the most important scientific work and literature reviews with relevance for the task of assessing the sustainability of innovations in agriculture.

Singh et al. (2012) provide an overview of sustainability assessment methodologies. They mention twelve approaches from four different fields that assess sustainability at the level of industries or technologies. The approaches are: (1) composite sustainability performance indices for industries; (2) product-based sustainability indices; (3) environment indices for industries; and (4) energy-based indices. But approaches based on life cycle assessments also play a role (Aistars 1999). Other reviews present international approaches to sustainability assessment (Grenz and Thalmann 2013) and provide an overview of sustainability assessment systems (Doluschitz and Hoffmann 2013).

Although the classical approach to sustainability comprises the three pillars of environment, economy and society, several authors suggest additional aspects of sustainability. Veleva and Ellenbecker (2001) suggest six main aspects of sustainable production: (1) energy and material use (resources); (2) natural environment (sinks); (3) social justice and community development; (4) economic performance; (5) workers; and (6) products. The authors adapt nine principles of sustainable production from the Lowell Center for Sustainable Production, provide recommendations for the development of indicators and suggest using a set of core and supplemental Indicators of Sustainable Production (ISP).

Rigby et al. (2001) present three facets of agricultural sustainability: (1) improved farm-level social and economic sustainability (enhances farmers' quality of life, increases farmers' self-reliance, sustains the viability/profitability of the farm); (2) improved wider social and economic sustainability (improves equity/is 'socially supportive', meets society's needs for food and fiber); and (3) increased yields and reduced losses (while minimizing off-farm inputs, minimizing inputs from non-renewable sources, maximizing use of (knowledge of) natural biological processes, and promoting biological diversity/'environmental quality').

Dunmade (2002) suggests a framework of indices to assess the sustainability of a technology[1] for introduction into a developing country. Adaptability is the primary indicator of sustainability of a technology and is evaluated using four secondary indicators, namely technical, economic, environmental and socio-political sustainability (Fig. 12.1).

[1] The terms technology (set) or best practice should be understood in the broadest sense possible as agricultural innovations, as *"an idea, practice, or object that is perceived as new by an individual or other unit of adoption"* Rogers (2003). Although the use of the word 'innovation' would be the most appropriate from the point of view of social science, the term 'technology' is commonly understood and frequently used by colleagues of other disciplines and extension practitioners. Keeping in mind the broad definition of innovation, in this chapter, we use the term technology as a synonym for innovation and best practice.

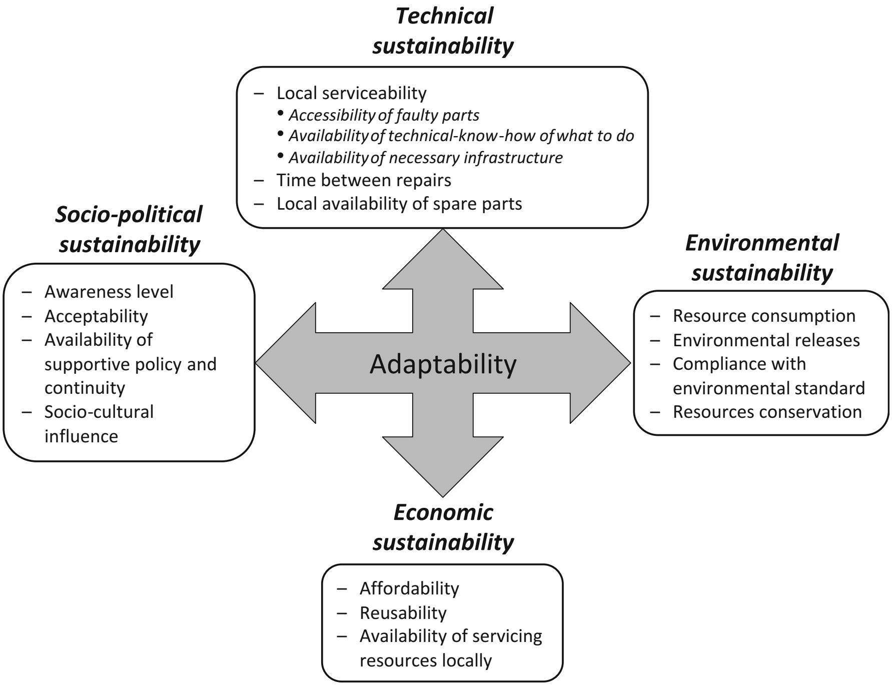

Fig. 12.1 Indices of foreign technology sustainability (Dunmade 2002, p. 464)

Dewulf and Van Langenhove (2005) describe a set of five sustainability indicators for the assessment of technologies based on industrial ecology principles. The indicators are: (1) renewability of resources; (2) toxicity of emissions; (3) input of used materials (reuse of materials); (4) recoverability of products at the end of their use (recoverability of waste materials); and (5) process efficiency. The indicators are based on the second law of thermodynamics. This allows for the quantification of all material and energy flows, exchange rates and conversion rates within a production system in exergy terms.

Dantsis et al. (2010) combine 21 individual indicators that cover the three pillars of sustainability (environment, economy, and society) into a unique indicator using the Multiattribute Value Theory (MAVT).

Many authors agree that sustainability is difficult to define (Kemmler and Spreng 2007). Therefore, Smith et al. (2000) inverse the approach and look at features of a system that are unsustainable, rather than searching for those that are sustainable. In their threat identification model (TIM), they first identify and rate potential hazards to sustainability depending on location-specific conditions, in particular, considering soil conditions and the risks of identified hazards. The final results are location-specific best management practice guidelines that can be developed for the farm level using GIS and that allow users to examine and understand the logic behind recommendations.

Analytical Framework

When analyzing the sustainability of an agricultural technology, the characteristics of the technology itself are of critical importance, because the speed and rate of adoption of an innovation depend on the personal characteristics of the potential adopter, the nature of the social system, the type of adoption decision, the extent of the change agent's promotion efforts and the specific attributes of the innovation itself that determine its usefulness for the potential adopter (Rogers 2003). Therefore, we consider four dimensions of sustainability in the analytical framework, namely the dimensions of environmental resilience, economic viability, social sustainability, and technical sustainability considering important properties of the innovation itself.

Criteria for Sustainable Agriculture

A literature search conducted at the end of 2012 resulted in the identification of 104 sustainability criteria relevant for agricultural technologies. These were reduced by merging similar indicators and deleting criteria with the same meaning but different terms, phrasing or unit of measurement, and eliminating indicators irrelevant for agriculture, or irrelevant in the context of developing countries. Criteria for which data collection would be too costly to collect were eliminated as well. As a result, 27 criteria were identified as highly relevant to the description of various aspects of technologies in the context of sustainability. Due to data limitations encountered during initial rounds of application of the framework, the criteria were further reduced, as shown in Fig. 12.2. The analysis aims to identify technologies that are sustainable, but also appropriate for the poor and vulnerable people, especially women and landless or land poor people. Such technologies are called suitable in this chapter. To address the special needs of poor and vulnerable people, two criteria are included that are not typically sustainability criteria, namely the minimum amount of land area required to adopt the technology and the percentage of female adopters as proxy for the suitability of the technology for vulnerable groups.

To decide on the relative importance of the criteria under consideration, experts were invited to provide weights for individual criteria using the Analytical Hierarchy Process (AHP) developed in the 1980s (Saaty 1990). This approach is a multi-criteria decision-making process that is suitable for involving a group of experts. It was implemented via an online survey that asked experts to compare all criteria in a pairwise manner. For each pair of criteria within the same sub-objective, experts

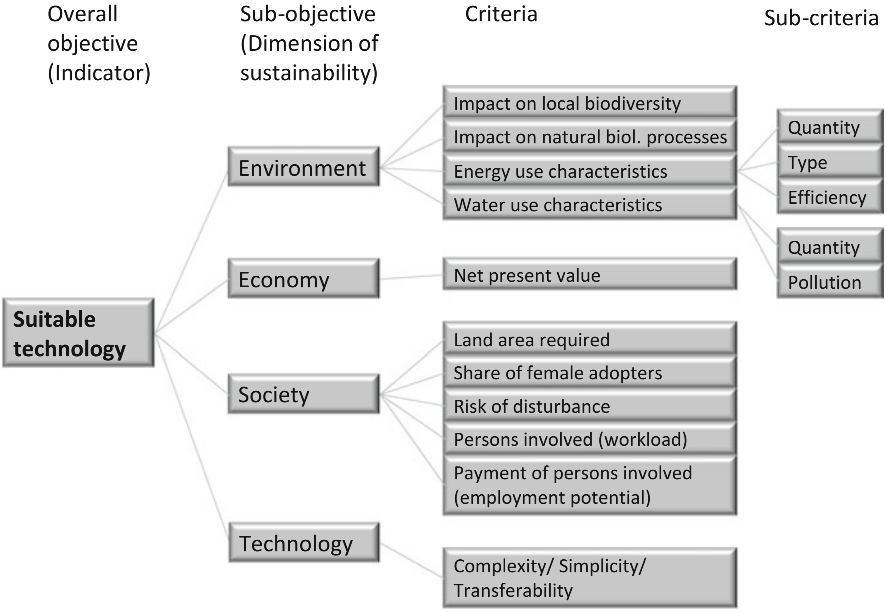

Fig. 12.2 Hierarchy scheme for analysis and composite sustainability indicator calculation

were first asked which criterion is more important or if they are of equal importance. If one was selected to be more important, experts were then asked how much more important the criterion is. Fifty-one experts were invited to participate in the online survey, out of which 12 took part (23.5 %). The results of this weighting exercise were ambiguous, probably due to the online survey format of the exercise. This format didn't allow for detailed personal oral presentation of the meaning of criteria to experts or questions and answers among survey participants. Although a written introduction was included at the beginning of the survey, the results revealed that respondents had a diverging understanding of some criteria. Further, the AHP method is prone to human error, especially with a large number of pairwise comparisons. For this reason, only five experts had consistency ratios below the recommended threshold. Based on these results, a criteria weight distribution was developed in consultation with a team of interdisciplinary scientists and project partners. Table 12.1 shows all essential criteria and the corresponding weights assigned to them by consensus.

To calculate the composite sustainability indicator, the sum of all weighted and normalized[2] criteria values was built:

[2] Where needed.

Table 12.1 Weights assigned to sub-criteria, criteria and sub-objectives of the framework

Sub-objective	Criteria	Weight		
		Sub-objective	Criteria	Sub-criteria
Environment	Water consumption	0.30	0.35	
	Water quantity			0.50
	Water pollution			0.50
	Energy consumption		0.35	
	Energy quantity			0.33
	Type of energy			0.33
	Energy use efficiency			0.33
	Impact on natural biological processes		0.15	
	Impact on local biodiversity		0.15	
Society	Number of people involved (workload)	0.30	0.15	
	Payment of people involved (employment potential)		0.15	
	Risk of disturbance		0.10	
	Share of female adopters		0.30	
	Land area required		0.30	
Economy	Net present value	0.30	1.00	
Technology	Complexity, simplicity, transferability	0.10	1.00	

$$CSI = \sum_{i}^{n} w_i \cdot cv_i, \tag{12.1}$$

where CSI is the composite sustainability indicator, w is the weight of criterion i, and cv is the criteria value of criterion i (compare Krajnc and Glavič 2005).

Application of the Tool

Detailed data was collected for 42 technologies, of which 30[3] were included in the data analysis presented here. The following questions were used for selection of technologies for analysis: (1) Can the technology be adopted by an individual or a single household? (2) Is the technology mature and has it been tested successfully in practice many times? (3) Is all information concerning the technology a public good

[3] Table 12.2 shows 32 data lines, because two technologies appear twice: the technology leasehold riverbed farming is considered using both original information from the expert and information gathered during an independent validation study on the technology. The sand-based mini hatchery can be used for either chickens or ducks. The tools and items needed for hatching duck or chicken eggs are identical, while handling and economic results differ slightly.

and does the technology have no patent right attached to it? Technologies for which all questions could be answered “yes” were included and are listed in Table 12.2.

Technologies for which no economic data was available were taken into account by using an average normalized net present value.[4] To make economic figures comparable, they were transformed into values per hectare of production. Conversion of monetary values from local currencies to US dollars was done using the OANDA online currency converter,[5] using the conversion rate of 31 March 2013. For criteria for which expert opinions were used, the data was compared among technologies and harmonized, where necessary. For instance, for the amount of water used, three answer options were available for experts to choose from: the technology uses (i) no water (0), (ii) little water (0.5), and (iii) large amounts of water (1). This left little room for distinctions between rainfed crops, intermittently irrigated, and flooded crops. Therefore, all technologies involving wet rice were assigned the score (1), all irrigated crops the score (0.5), and rainfed crops the score (0.2). Where necessary, data was normalized before analysis.

Three technologies will be presented in more detail, namely vermitechnology, broom grass farming on marginal lands, and the mini hatchery model for chickens.

Vermitechnology is a process which uses earthworms to produce good quality compost (vermicompost) through organic waste recycling. The commonly used earthworms include *Eudrillus* sp. *Perionyx* sp., *Eisenia* sp. or any locally-available earthworms living and feeding on the surface of the soil (epigeic worms). A tank of $5 \times 1 \times 1$ m allows about 500 kg of waste to be composted through the activity of worms and microorganisms, producing about 250–300 kg of compost over approximately 1 month. Vermitechnology can either be practiced in tanks or in the ground. However, the major advantage of a tank is the efficiency of composting and keeping the worms captured. The technology requires little investment and technical know-how.

Broomgrass (*Thysanolaena maxima*) is a perennial, high-value, non-perishable Non-Timber Forest Product (NTFP) that can be grown on degraded, steep, or marginal land. Broomgrass is a multipurpose crop: only its panicle is used for brooms. The stems are used by farmers as construction material, fuel, fodder, mulching, or staking crops, or sold to the pulp industry to manufacture paper. The leaves and tender shoots are used as fodder in times of scarcity. Broomgrass farming can generate additional income through cultivation on marginal lands unsuitable for food production. It can also be used as part of an agroforestry system to regenerate degraded land.

A sand-based ***mini-hatchery*** uses a simple wooden incubator to hatch chicken (and duck) eggs in rural areas to assure a regular supply of chickens (and ducks) for income and food security. The heat that is needed to brood the eggs comes from

[4] These technologies are tomato grafting, treadle pump and micro irrigation technology, vermitechnology, windmill, chili and sweet pepper grafting, school gardens, crotalaria, and rainbow trout aquaculture.

[5] http://www.oanda.com/lang/de/currency/converter/.

kerosene lamps: the sand helps to retain and distribute the heat evenly inside the insulated cabinet. Besides the wooden cabinet and wooden or metal trays and racks, it uses cheap local materials such as quilts, sand that can retain the heat, jute sacks, and kerosene. The incubator should be placed in a separate hatchery room. It can assure a regular supply of 1-day-old chickens (or ducks) for income and food security in rural areas.

Results

Technologies are grouped into more suitable and less suitable technologies based on a non-hierarchical cluster analysis (K means) of the Composite Sustainability Index (CSI) (Table 12.2). Groups A to C represent the 13 most suitable technologies based on the data presently available and the analytical assumptions made. Looking at three exemplary technologies, the CSI ranks vermitechnology as the most suitable, followed by broom grass farming, and the mini hatchery for chickens.

The radar chart (Fig. 12.3) reveals more details on the performance of the three examples, vermitechnology (*green line*), broom grass farming (*blue line*), and mini hatchery (*red line*). If the line is close to the outer edge of the diagram, the technology is performing well in terms of the particular criterion. All technologies can be seen to be performing relatively well in terms of water consumption.

The hatchery hardly uses any water (for cleaning only), broom grass farming is a rainfed culture and vermitechnology needs little water to keep the substrate in which the earthworms live and upon which they feed moist. Only the hatchery uses a little energy, which comes, however, from a non-renewable source in the present state of technology design. It has no impact on biological processes, while broom grass prevents soil erosion and vermitechnology positively impacts nutrient cycling. Vermicompost has a better impact on biodiversity than the mini hatchery and broom grass farming. The latter performs not so well in terms of biodiversity, because land areas that were formerly covered with a diversity of wild plants are then cultivated with broom grass alone. All technologies require little input in terms of work; broom grass cultivation even creates local jobs in peak times. None of the compared technologies has a risk of disturbing the neighborhood or creating social conflicts. All technologies are suitable for female adopters, but broom grass farming involves some hard work to prepare the soil during the planting period. The hatchery and vermitechnology can be practiced on a few square meters of land, while only broom grass should be practiced over more extended areas. The composite sustainability indicator is calculated with an area of at least 200 m^2. According to the vermitechnology expert, farmers can sell one kg of compost for 50¢ (US). With initial investment costs of about $50 (US) for a tank that covers 5 m^2, and considering some additional space for charging and discharging the tank, the figures lead to a net present value per hectare of $4.78 million (US) for a 5 year period at 1.5 % interest. This is by far the highest NPV per hectare for the set of technologies included in the analysis. For comparison, the 5 year period NPV of

Table 12.2 Sustainability clusters of selected technologies

Group	Technology name	CSI	Note
A	Vermitechnology	0.494	*example*
B	Vegetable pool	0.15 – 0.23	
	Organic vegetable production in sack		
	Bio intensive school gardens		Mean NPV
	Domestic yam production		
	Stinging nettle for enhancing animal productivity		
	Ecological sanitation		Mean NPV
	Crotalaria against nematode damage of chili		
C	EFSB IPM, Bangladesh (summer + winter crop)	0.10 – 0.13	
	Broom grass farming on marginal lands		*example*
	Backyard poultry farming		
	Sugiharto organic fertilizer (if cows are already available)		
	Leasehold riverbed vegetable production		
D	Treadle pump and micro-irrigation technology for smallholders	0.06 – 0.095	Mean NPV
	Windmill		Mean NPV
	Floating vegetable garden		
	Leasehold riverbed vegetable production (validated)		
	Floating cultivation on organic bed		
	Cricket farming		
	Sandbar vegetable cultivation technique		
	Non chemical IPM technology package for tomato cultivation		
	Hybrid tomato seed and tomato production		
E	Mini hatchery for chickens	0.03 – 0.05	*example*
	Mini hatchery for ducks		
	Open cultivation of off-season tomatos		
	Chili and sweet pepper grafting		Mean NPV
	Integrated rice-duck farming technology		
	Tomato grafting		
F	Cage fish culture	−0.07 – −0.01	
	Improved Kharif paddy production system		
	Improved cultivation of rainfed maize-based cropping systems		
	Himalayan rainbow trout aquaculture technology		Mean NPV

Note: technologies with "*example*" in the right column are presented in more detail in this chapter

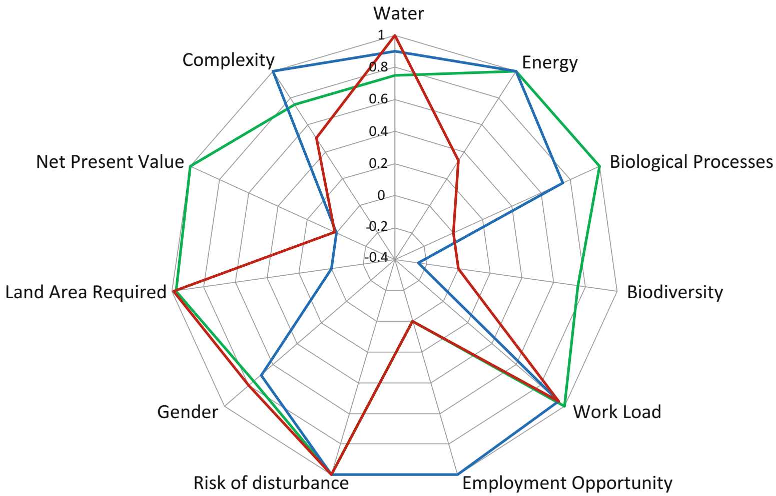

Fig. 12.3 Suitability radar chart for vermitechnology (*green*), broom grass farming (*blue*), and mini hatchery (*red*)

broom grass farming and the mini hatchery is $1,881 and $50,016 (US), respectively. From the amount of knowledge and skills a person has to master for successful operation, the mini hatchery appears to be the most complex and broom grass farming the easiest of the three technologies.

Limitations of the Framework

Although the objective of identifying suitable technologies is soundly justified and well-grounded, there are several inherent issues and limitations that need to be kept in mind when interpreting results and formulating extension recommendations on the suitability of technologies.

Firstly, the analytical framework presented in this brief should not be considered a tool for comparing the sustainability of different technology types against each other. Rather, it provides information on various aspects of sustainability for a given technology and can serve as a decision tool for comparing different but related technologies with each other.

Secondly, combining biophysical information with social and economic information into a single indicator carries the inherent problem of incommensurability between different dimensions of sustainability (Rigby et al. 2001). Another issue in respect to composite indicator calculation relates to compensation between the values of its components. For instance, low or no energy consumption cannot balance a high use of water or a low net present value. However, this issue can be overcome by looking at the underlying data that can be presented visually with radar charts.

Also, our assessment is based on inputs (e.g., energy and water), rather than actual sustainability outcomes. This is due to the limited availability of impact data. *"It is commonly the case that assessments of sustainability operate by prediction rather than direct evaluation of impact. ... One of the key issues is the extent to which one can map with confidence from inputs to environmental impact."* However, we, as others, believe that the assumptions that we have made on impacts are, while crude, nevertheless robust (Rigby et al. 2001).

Future Research Needs

The research presented here is not final, results present the current state of knowledge, and data and efforts should go on to further increase the data set and refine the methodology. More sophisticated criteria, like the actual amount of water used, waste water produced, actual amounts of inputs and outputs, from recycled farm materials or from offsite, could be included if reliable data could be traced for all technologies. The effort by local experts to collect necessary data for sustainability analysis, and the exchange with the Food Security Center (FSC) to fill data gaps and validate expert data and opinions is ongoing. Furthermore, when additional technologies are included in the comparison, normalized variable values are likely to change, affecting the overall results. For this reason, the presented results are based on the best data available to date. Future findings might change the sustainability ranking and grouping of technologies. Newly emerging tools, like the SAFA small App tool (FAO forthcoming[6]), will allow for cross-checking and validating the generated results when compared with each other.

[6] http://www.fao.org/nr/sustainability/sustainability-assessments-safa/safa-small-app/en/.

References

Aistars GA (ed) (1999) A life cycle approach to sustainable agriculture indicators. In: Proceedings. The center for sustainable systems, University of Michigan, Ann Arbor, p. 118

Dantsis T, Douma C, Giourga C, Loumou A, Polychronaki EA (2010) A methodological approach to assess and compare the sustainability level of agricultural plant production systems. Ecol Indic 10(2):256–263. doi:10.1016/j.ecolind.2009.05.007

Dewulf J, van Langenhove H (2005) Integrating industrial ecology principles into a set of environmental sustainability indicators for technology assessment. Resour Conserv Recycl 43(4):419–432. doi:10.1016/j.resconrec.2004.09.006

Doluschitz R, Hoffmann C (2013) Überblick und Einordnung von Bewertungssystemen zur Nachhaltigkeitsmessung in Landwirtschaft und Agribusiness. In: Hofmann M, Schultheiß U (eds) Steuerungsinstrumente für eine nachhaltige Land- und Ernährungswirtschaft. Stand und Perspektiven, KTBL Schrift 500. Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V, Darmstadt, pp 34–47

Dunmade I (2002) Indicators of sustainability: assessing the suitability of a foreign technology for a developing economy. Technol Soc 24(4):461–471. doi:10.1016/S0160-791X(02)00036-2

FAO (1995) FAO trainer's manual, Vol. 1: sustainability issues in agricultural and rural development policies. Food and Agriculture Organization of the United Nations, Rome

Godfray HCJ, Beddington JR, Crute IR et al (2010) Food security: the challenge of feeding 9 billion people. Science 327(5967):812–818. doi:10.1126/science.1185383

Grenz JAN, Thalmann C (2013) lnternationale Ansätze zur Nachhaltigkeitsbeurteilung in Landwirtschaft und Wertschöpfungsketten. In: Hofmann M, Schultheiß U (eds) Steuerungsinstrumente für eine nachhaltige Land- und Ernäh-rungswirtschaft. Stand und Perspektiven, KTBL Schrift 500. Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V, Darmstadt, pp 23–33

Kemmler A, Spreng D (2007) Energy indicators for tracking sustainability in developing countries. Energy Policy 35(4):2466–2480. doi:10.1016/j.enpol.2006.09.006

Krajnc D, Glavič P (2005) A model for integrated assessment of sustainable development. Resour Conserv Recycl 43(2):189–208. doi:10.1016/j.resconrec.2004.06.002

Rigby D, Woodhouse P, Young T, Burton M (2001) Constructing a farm level indicator of sustainable agricultural practice. Ecol Econ 39(3):463–478. doi:10.1016/S0921-8009(01)00245-2

Rogers EM (2003) Diffusion of innovations, 5th edn. Free Press, New York

Saaty TL (1990) How to make a decision: the analytic hierarchy process. Eur J Oper Res 48 (1):9–26. doi:10.1016/0377-2217(90)90057-I

Singh RK, Murty HR, Gupta SK, Dikshit AK (2012) An overview of sustainability assessment methodologies. Ecol Indic 15(1):281–299. doi:10.1016/j.ecolind.2011.01.007

Smith C, McDonald G, Thwaites R (2000) TIM: assessing the sustainability of agricultural land management. J Environ Manag 60(4):267–288. doi:10.1006/jema.2000.0384

UN (2012) The future we want. Resolution 66/288. United Nations, Geneva

Veleva V, Ellenbecker M (2001) Indicators of sustainable production: framework and methodology. J Clean Prod 9(6):519–549. doi:10.1016/S0959-6526(01)00010-5