A Stock and Flow Based Framework for Indicator Identification for Evaluation of Crop Production System

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Abstract

Crop production and crop yield has been the sole focus of most of the existing agricultural policies and interventions, which has resulted in several undesirable outcomes over a long term. To evaluate any production system holistically, it is necessary to identify a set of indicators accounting for economic, social and environmental dimensions. While the existing indicator selection frameworks help in identification of indicators, they lack a logically structured and transparent process. In this work, we develop a stock and flow based framework for a systematic selection of indicators for evaluating crop production systems. Stock and flow diagrams are used for conceptualization of the system and are sorted with respect to material, energy, and financial flows associated with the system. Various causal flows and their linkages are traced for each of the input-output component, and one representative indicator is selected for each causal flow. The indicators associated with desirable outcomes are taken in terms of input-output efficiency while undesirable outcomes are considered in terms of their absolute values. Using this process, a set of thirteen indicators have been identified for assessing the viability of agricultural practices with respect to socio-economic and ecological sustainability.

Keywords: Systems Thinking, Stock and Flow Diagram, Indicators, Framework, Agricultural Policies
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1. Introduction

Increasing population and food demand has always kept the agricultural production under pressure. Public policies as well as technology focuses only on increasing the production specifically by improving the yield of crops. The notion of productivity has been associated only with the crop yield, which in turn is linked only with the fertilizer applied to the field or improvement in crop variety. While these misconceptions have lead to inappropriate use of synthetic fertilizers by farmers, scientific community has been focused mainly on technologies to improve crop yields. This reductionist approach has lead to the negligence of the role of other management practices like mulching, manure application etc. for increasing the productivity of farming. It has become the nature of conventional farming practice to focus on short term output benefits which has obscured the impacts caused to environment and soil quality. Agricultural policies have not only deteriorated the biophysical sustainability of agriculture, it has affected the financial remunerativeness of the farming itself in longer run.

Scientific research has been moving more towards specialization and often leading to a narrowed approach. Researchers keep deepening the knowledge in a specific area and are losing focus on the phenomena or system as a whole. Due to this, technological interventions for societal problems are often unidirectional and are focused towards short term goals. While short term goals might be well achieved, there can be many unseen side-effects caused due to these interventions during its long run.

In a similar context, it is a fundamental problem that the performance of agricultural system is being interpreted only based on crop yield while neglecting the un-targeted outcomes. It is becoming inevitable that we need to consider all undesirable outcomes and hidden/long term changes (like land degradation, health impact of the pesticide residues etc.) through a comprehensive assessment focused on all aspects of the system. This demands a detailed consideration of various economic, social, and environmental impact indicators of the agricultural system, with proper accounting of various resources utilized, in order to promote appropriate technologies and practices.

Research groups from various regions had used different methodologies with different objectives to evaluate the agricultural system. While almost all methodologies have the sustainable agriculture as their focus, the interpretation of concept of sustainable agriculture is itself subjective. The concept of sustainable agriculture has evolved as the management and utilization of agricultural ecosystem in a manner which maintains its biological diversity, productivity, regeneration capacity, vitality, and ability to function at the local, nation and global levels without any harmful effects on other ecosystem (Lewandowski et al., 1999). In general, the concept of sustainability has revolved within the notion of environmental dimension neglecting socio-economic aspects of the farm. Studies had missed the multi-functionality of agriculture and the applicability of results (Binder et al., 2010). This has obscured the interest of small and marginal farmers which is crucial for any developing country.

India has more than 80% of its farmers, which essentially means, about 500 million people depend on farming for their livelihood with less than 2 hectare land holding (State of Indian Agriculture 2012-13). Remunerativeness of agriculture for such a population plays a very crucial role for the socio-economic viability of Indian agriculture. So a farming practice can be remunerative when it is affordable and gives substantial income for their basic survival including food, shelter, health and education, and provide them the financial stability to undertake farming for next cropping season. So, our focus is to design a methodology for assessing the viability of agricultural practices with respect to socio-economic and ecological sustainability. In this paper, we start with a brief note over the basic approach in assessing an agricultural system, application of systems thinking in agriculture and recent development in indicator selection methodology followed by description of the proposed framework based on stock and flow diagram for indicator selection and its application on agricultural system.

1.1. Assessment of agricultural system

A variety of assessment tools has been developed in past for evaluating production system which includes Life Cycle Assessment (LCA), Cost-Benefit Analysis (CBA), Environmental Impact Assessment (EIA) and Principles, Criteria and Indicators (P,C&I). P,C&I method is being used widely for assessment of environmental sustainability of agriculture. In this technique, a set of principles are identified and structured thematically based on the system under study and objective of the study, followed by identification of criteria for indicator selection and finally indicators are selected through causality relations(Van Cauwenbergh et al., 2007).

An indicator is a "sign or signal that relays a complex message, potentially from numerous sources, in a simplified and useful manner" (Jackson et al., 2000). Indicators are principally the means to characterize the status of the system, which can be monitored subsequently to predict changes in the system. Indicators are usually a perceivable biological or chemical or physical or socio-economic attribute of the system. For a comprehensive assessment, it is desirable to have least uncertainty over the system by accounting all possible components and processes, but it might lead us to a cumbersome number of indicators to be monitored and evaluated. The cost, time and complexity involved in handling a large number of indicators necessitate the need to limit the indicator set (Pannell and Glenn, 2000). The credibility of indicators selected is crucial for the validity of assessment reports and so the process of indicator selection should be rigorous and transparent. This necessitates the need for robust methodology for selection of indicators (Dale and Beyeler, 2001). Although the existing frameworks help in identification of indicators, it does not have a structured process for indicator selection and the process lacks social inclusiveness and transparency (NCSSF, 2005).

So, a methodological framework is essential to legitimize and systematize the process of indicator identification and selection. In this study, the indicators are selected to comprehend socio-economic and environmental dimension of agricultural system, which will aid our understanding of state of the system and assist in policy making on issues like subsidies, design of schemes, funding agricultural research.

1.2. Systems thinking in agriculture

Systems thinking can bring together the researchers, administrators, beneficiaries and other stakeholders for a collective decision making process (Hopkins et al., 2012). Systems approach is being widely applied in various managerial problems for aiding decision making and policy recommendations. The concepts of causal-loop diagram and stock and flow diagrams are simple and powerful tools for system analysis (Chang et al., 2008).

System dynamics is often used in the context of ecological agriculture or organic farming where simulations are used to predict future scenarios considering long term impacts of agricultural practices. For example, the long term trend of the ecological and economic effects of eco-agriculture of Kongtong District, Pingliang City, Gansu Province, China, has been simulated from 2008 till 2050. The system shows improvement till 2027 where it reaches its peak and after which it gradually declines. Excessive cattle slaughtering, unstable methane production, sluggishness in development in organic agriculture and unsustainable energy structure are found to be the major defects and disadvantages of the eco-agriculture system (Li et al., 2012). A system dynamics based Agricultural-Institutional-Social-Ecological-Economic Model (AISEEM) was developed to gain insights over the dynamics of politics, economics and environment involved in the ecological agricultural development of Jinshan County. The results showed that the institutional arrangements and capacity building play an important role for the adoption of any technology by farmers. Diversification of land use, low interest loans and government supported training programs are found to be the major policy measures for sustainable development of ecological agriculture (Shi and Gill, 2005). Becu et al. (2003) has observed that objective of simulations is to explore the implications of alternative management approaches rather than providing accurate prediction of future scenarios.

Similarly, systems approach has been used to model multi-functionality of agriculture where the role of agriculture in production of commodities (food, fodder etc.) and non-commodities (ecological services, tourism etc.) are accounted (Johnson et al., 2008). Integrative models which combine various goals of multifunctional agriculture ((Groot et al., 2007) (Dogliotti et al., 2005)) had focused more on methodology development with limited attention to model evaluation and application. They are often found to have an unbalanced accounting of socio-economic and ecological dimensions depending upon the nature of stakeholder. The results from model feeds back into the model which in turn improves the description of the system. Thus the contribution of integrative modeling can be fruitful in refining the definition of indicator set or systems (Rossing et al., 2007). In similar context, we propose to use systems thinking, and stock and flow diagrams for identification of suitable indicators for assessing the sustainability of farming and farmers' livelihood.

1.3. Systems thinking in indicator identification

Application of systems approach for the selection of indicator is not very new concept as (Bossel, 2003) has proposed a systems framework where every system is hypothesized to have a subsystem within it and environment around it. At any state of the system, there exist six balancing phenomena (orientors and orientation) between system and subsystem. This renders subsystem-system-environment under equilibrium. While in theory, this framework appears to give a comprehensive description of the system by capturing all essential phenomena effectively, in practice, it is too complex to be applied to most systems.

While most of the conceptual framework used in environmental assessment like Pressure-state-response (PSR) or driving force-pressure-state-impact-response (DPSIR), roots itself in causal chain of individual processes, the recently developed, enhanced driving force-pressure-state-impact-response (eDPSIR) framework uses the causal network where multiple causal chains and their interactions are considered. The causal network provides conceptual guidance for understanding the complexities of real world and helps in achieving a relatively systemic and transparent process of indicator identification (Niemeijer and de Groot, 2008).

While the use of DPSIR terminology has been widely found in environment centric sustainability literature, application of the concept of stock and flow diagram (SFD) broadens the scope of the framework. SFD helps in better understanding of system under study and strengthens the knowledge over the nature of variables. Further, in eDPSIR framework, the final selection of indicators is subjective and majorly depends on the selection criteria applied to the indicators identified using causal network. In the proposed framework based on SFD, we have identified a set of generic principles which needs to be applied for the selection of appropriate indicators from the identified indicators.

2. Indicator Selection Framework

The choice of indicators forms the basis of evaluation of any production system. As discussed earlier, the process of indicator identification and selection should be rigorous and transparent. Therefore, it is necessary to have a methodological framework to legitimize and systematize the process.

2.1. Conceptual framework

A conceptual framework is a virtual platform built to guide any research process by adding rigor to an idea or a concept. In this work, the role of the framework is to facilitate the identification of exhaustive list of indicators and ensure the selection of core, coherent, and consistent list of indicators.

2.1.1. Stock and flow diagram

In order to assess the sustainability of any production system it is important to include variables characterizing long term impacts of various processes in the system. The existing frameworks are focused on the causal linkages but do not explain the nature of variables. Conceptualization of the system using stock and flow diagram (Sterman, 2000) will help in differentiating the variables where stocks describe the characteristics of the system that are accumulated over long term, and flows describe the transient and short term characteristics of the system. The stock and flow diagrams (SFD) with all significant processes and phenomena of the system can be the conceptual model for visualizing various independent and interdependent processes. The demarcation of material, energy, labor, economic and information flows involved in the complex system will further help us in understanding the functionality of system.

2.1.2. Understanding the stock and flow in the system

In general, any production process involves material, energy and information inflow which eventually results in a variety of outputs and outcomes. While the inflows to the system are the resources consumed, the outflow can have unintended outcomes along with the intended outputs. The unintended outcomes (whether within or outside the system) can either be beneficial or harmful. In environmental sustainability literature, outcomes are mostly contextualized with respect to the environment only and are referred as beneficial or harmful impacts (OECD, 1999). But the impacts in crop production system are both within the system (field under cultivation) as well as in the environment (surroundings other than the field). Further the impacts within the system (field under cultivation) plays a crucial role in sustainability of farming. The inflows to field include materials like seed, water, fertilizers, etc. resulting in the intended outcomes of food, fodder, fiber and fuel, along with unintended ecological services, degradation etc. Stock variables describe the state of system at any given time and are the accumulation of all past impacts over their initial state. So, stock variables should be the major focus to account for the long term effects.

2.1.3. Construction of the conceptual system

The initial step in construction of the stock and flow diagram is defining the system and its boundary. In this work, the field in which the crops are being cultivated is taken as the system and the physical boundary of the field is taken as the system boundary. Construction of stock and flow diagram begins with identification of relevant processes followed by the identification of stocks in individual process (Wolstenholme, 1983). The modelling is an iterative process with delineation of each process resulting in introduction of new stocks, flows, and auxiliary variables. This in turn brings focus on yet unconsidered processes involving more variables. All possible feedback loops in the system need to be identified as they are crucial for system equilibrium (Wolstenholme and Coyle, 1983). The minimum temporal scale for the evaluation of agricultural system is one cropping season as it represents the unit period of flow cycle.

2.2. Identification of indicators

Although almost all the variables in the stock and flow diagram can be taken as indicators, a large collection of mutually dependent variables may not convey the essence of the system. It is necessary to capture the state of the system in totality while avoiding over/under accounting of important system characteristics. Therefore, it is essential to systematize the process of indicator identification from the stock and flow diagram.

2.2.1. Basis for identification of indicators

In any production system, short term desirable outcomes (often flow variables) are of the major focus while several undesirable outcomes which get accumulated in stock are neglected. In case of agriculture, conventional indicators like yield and income are flow variables that capture only the immediate outcome of crop production process and fail to capture the outcome accumulated over a long term by the farm as a system. A system can be considered to perform better if there is either an increase in desirable outcome or a decrease in undesirable outcomes. In order to evaluate the performance of any system with respect to its desirable outcome, it will be appropriate to measure their output efficiency with respect to the inputs (Jahanshahloo et al., 2012). In case of undesirable outcomes, use of efficiency measure will result in the goal of maximum reduction of the undesirable outcomes. But reducing these undesirable impacts to its minimum level may not be feasible as it may work against the main purpose of the system. So, it will be appropriate to have an objective of restricting the undesirable outcomes within the safe limits or permissible standards which are determined through scientific studies. In certain cases, undesirable outcomes of the most efficient system can be considered as a benchmark but in many scenarios, even an efficient system may or may not be the most favorable or sustainable state of the system.

In short, the indicators associated with desirable outcomes needs to be measured in terms of input-output efficiency while undesirable outcomes need to be measured in terms of absolute quantifying variables. With this basis, indicators can be associated with input and output variables of the system. So, extraction of input-output relationship of each process involved in the system will give a set of abstract and essential indicators that need to be accounted for evaluation of the system.

2.2.2. Selection of indicators

The input-output flows need to be extracted from the stock and flow diagram of the system and sorted with respect to material, energy, and financial flows associated with system. Following it, various causal flows and their linkages need to be traced over the stock and flow diagram, and one representative indicator is selected for each of the causal flow in the input-output component. For example, as we will be discussing in later section, crop harvested is a single output, but both nutrient flow and water flow are inputs to the crop production process, which necessitates the selection of nutrient efficiency and water efficiency as separate indicators. There are two scenarios where selection of indicators may be challenging.

In case of any phenomenon or causal flow that cannot be directly measured or when an indicator demands complex protocols for its estimation, a suitable proxy variable needs to be considered. A proxy variable should be a variable which is highly correlated and representative (if not a substitute) of the variable of our interest. For example, soil structure is too complex to quantify and so, the soil porosity can be taken as a proxy indicator. However, proxy indicators must be in close approximation to the target indicator with a similar dynamic function.

In case of variables associated with more than one process, or more than one variable in single process, appropriate measures need to be taken to avoid over/under accounting of any characteristics of the process. In such scenarios, stock and flow diagram can facilitate the selection of indicators, where the causal flow and their linkages are traced for a suitable variable. To deal with the variables with multiple linkages, two strategies can be applied depending upon the situation. One can either trace the variable backward or forward on the causal flow to capture the concerned flows individually, or, one can introduce additional indicators as correction factors which will compensate for the errors caused by the other indicator. For example health impacts of pesticide usage on humans may be the target indicator but it cannot be accounted directly as health is influenced by various other factors outside the system boundary. In such cases, SFD helps us to trace the causal relations of health impact to factors like pesticide contamination in water bodies, accumulation of pesticide residues in food, physical exposure to pesticides etc., that are in turn traced back to the amount of pesticides applied, which can be taken as proxy indicator. However, appropriate measure needs to be taken in order to minimize error. So, a suitable mathematical function of the amount of pesticide applied can be taken as a substitute for the health impact indicator. In the next section we employ this framework to identify indicators for crop production system.

3. Identification of Indicators for Crop Production System

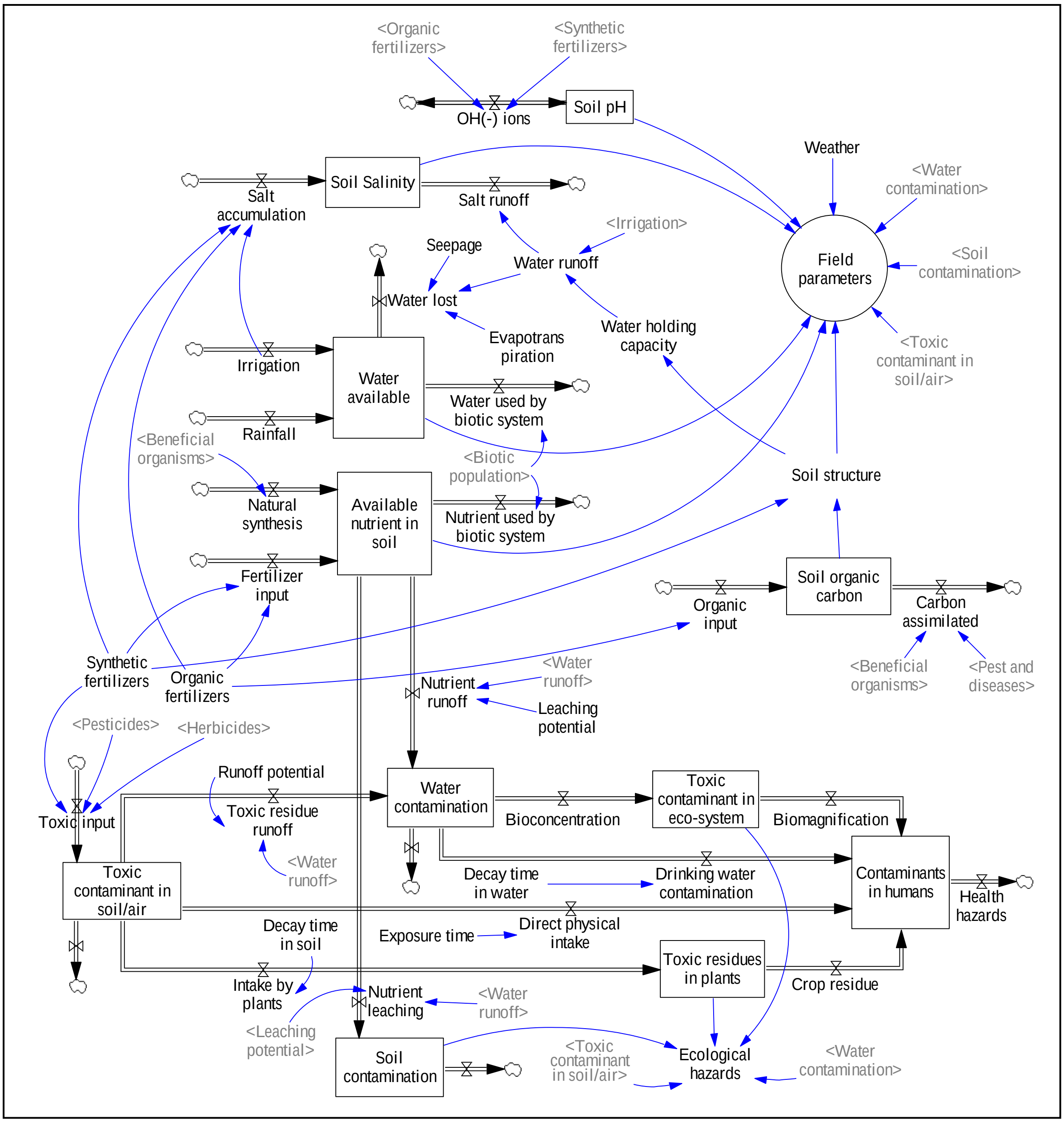

Figure 1: Material flows in abiotic system of crop production

The stock and flow diagrams for material, energy and financial flows for crop production system were constructed to identify a suitable set of indicators. Since our objective is to conceptualize the system rather than dynamic simulation, the stock and flow diagrams are built to show only the essential factors and linkages involved in the system. The material flows in abiotic and biotic ecosystem are captured in Figures 1 and 2 respectively. Figure 1 shows the effect of farm inputs to field parameters like available soil nutrient, available water etc., including the undesirable impacts caused by farm inputs.

The biotic system (Figure 2) has four aggregated stocks including crops, weeds, beneficial organisms, and pest and diseases, which are strongly interlinked with each other. Energy and financial flows involved in crop production process are captured in Figure 3 and 4 respectively. In case of financial flow, total financial resource available with farmer and living expenses are considered to account for the remunerativeness for farmer and financial viability of the crop production system.

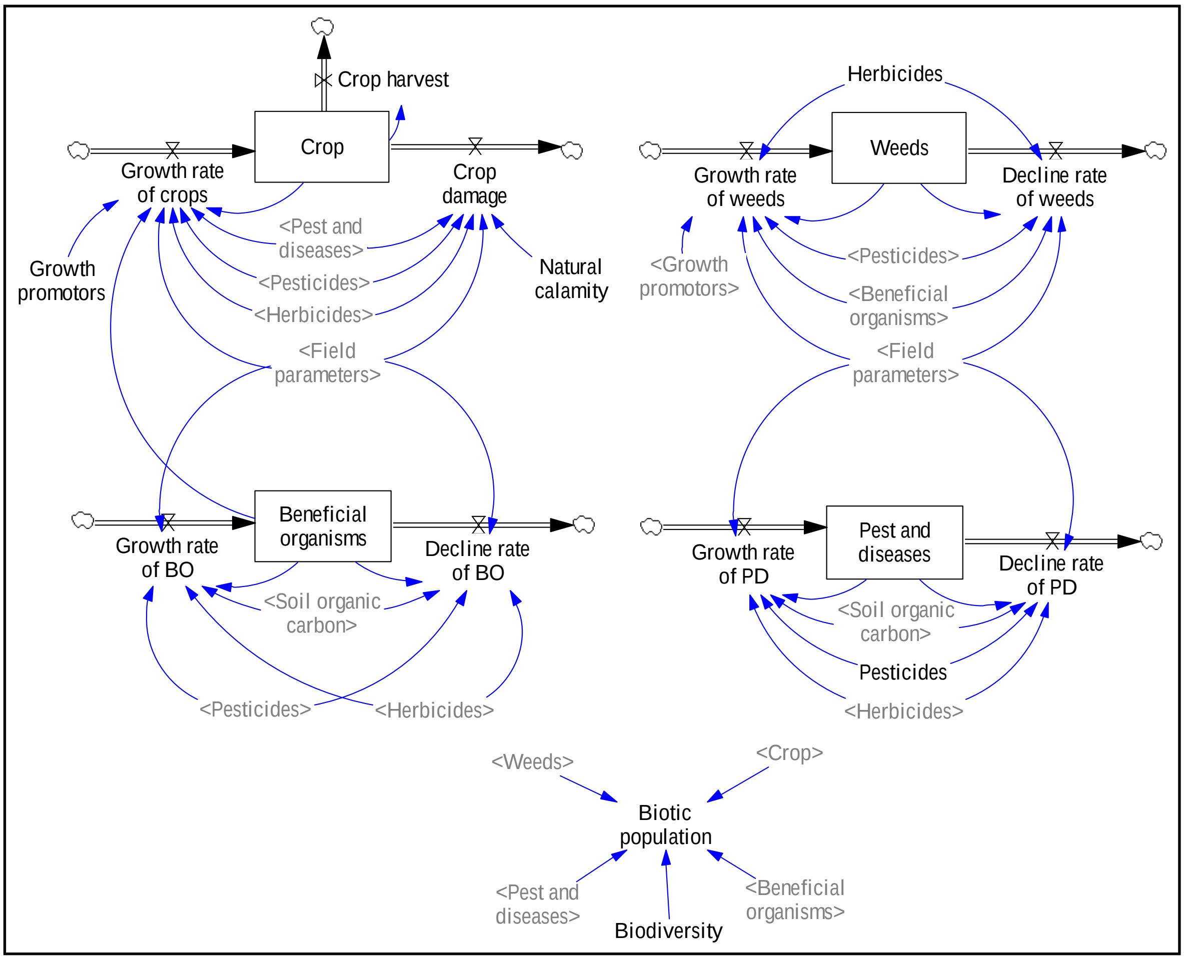

Figure 2: Material flow in biotic system of crop production

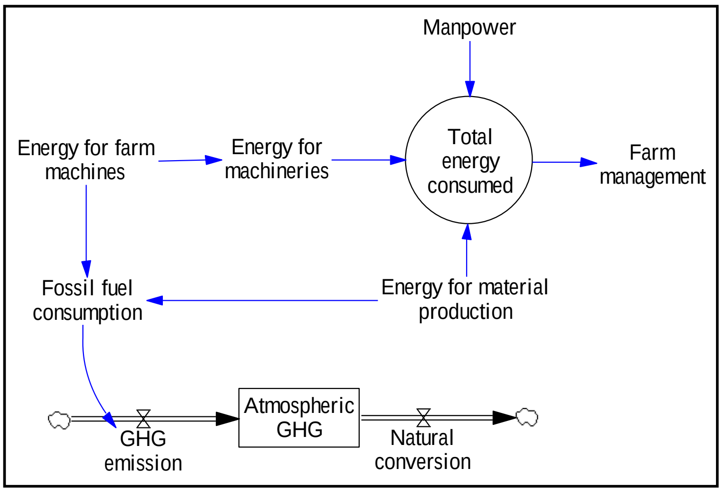

Figure 3: Energy flow in crop production system

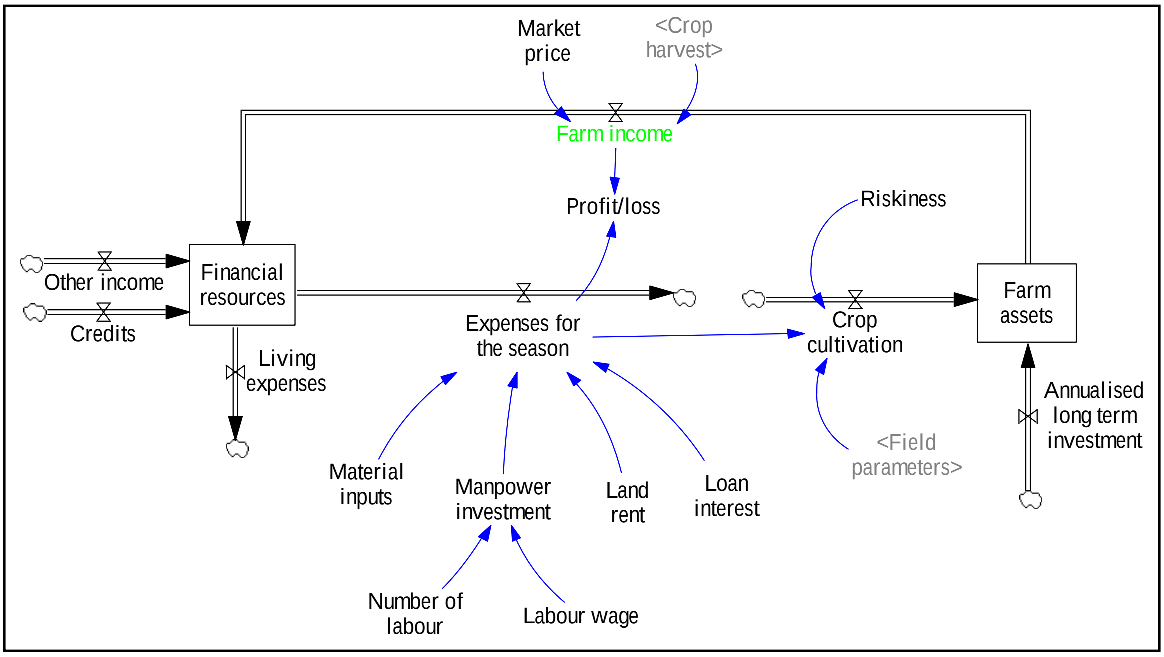

Figure 4: Financial flow in crop production

Following the construction of stock and flow diagram, as per the methodology described in Section 2.2.2, all the input and output variables of the system were identified as shown in Table 1. The input and output variables are captured with respect to material, energy and financial flow, and appropriate indicators are selected.

In material flow diagram (Figure 1), conversion of nutrient and water stock to crop production is the desirable output, which is affected by the field parameters and other biotic components (shown in Figure 2). Although there are several other desirable outcomes like control of pest by pesticide application, its effect is reflected as increase in crop production, and so a separate indicator is not required.

Table 1: List of inputs and outputs of the crop production and their corresponding indicators for evaluation

S No	Component	Input	Desirable outcomes	Indicators	Undesirables outcomes	Indicators	Proxy indicators
1	Material flow	Water	Crop harvest and Crop residue harvest	*Water use efficiency*			
		Fertilizers		*Nutrient use efficiency*	Increase in salinity	*Salinity*	
					Deviation from normal soil pH	*pH*	
					Accumulation of toxic contaminant	Toxic concentration	*Fertilizer impact quotient (**FIQ)*
					Soil contamination	Soil contamination	
					Water contamination	^^Water contamination	
					Soil structure		*Soil porosity*
		Pesticides and herbicides			Direct residual intake	Producers health impact	*Pesticide impact quotient (**PIQ)*
					Toxic residues in produce	Consumers health impact	
					Drinking water contamination	Toxic content in drinking water	
					Ecological impacts	Toxic content in ecosystem	
					Water contamination	^^Water contamination	
					Reduction in biodiversity	*Biodiversity index*	
2	Energy flow	Fuels used in machineries and production of farm inputs			Air pollution	GHG emission	*Fossil fuel used*(in fertilizer production and farm machines)
		Manpower	Employment	*Employment*	Labour (If employment was not considered)	Labour efficiency	
3	Money	Expense for the season	Income	*Cost-Benefit ratio*	Seasonal expenses (Viability of farming)	*Affordability*	
		Long term investment			Debt (Remunerativeness)	*Riskiness*	
Note	^^ indicators which are affected by two different flows ** indicators which accounts more than one process or flows						

Undesirable outcomes are found both in the environment as well as within the system. All the outcomes that are potentially harmful to either ecosystem as a whole or directly to human needs to be accounted for. While the impact of input on the field parameters like pH and salinity can be measured directly, variables outside the field boundary like ecological hazards and health hazards are difficult to measure in practice due their complex relationship with various inflows. So, proxy variables like fertilizer impact quotient and pesticide impact quotient are used to account for several undesirable impacts, as given in Table 1.

Similar to Environmental Impact Quotient (EIQ) developed by (Kovach et al., 1992), Pesticide Impact Quotient needs to be designed with the help of comprehensive toxicological database of pesticides, for addressing the concerns of farm worker, consumer, wildlife and eco-system. In case of energy flow, the level of detail considered for various processes depends on the availability of data. One practical way of measuring the energy consumed is to convert various means of energy used into its fossil fuel equivalent and take the corresponding GHG emissions as the total undesirable outcome in energy flow of the system. While the labor involved may be considered as desirable outcome by the government, the farmers may consider it as a cost to be minimized. So, the manpower can be considered either as employment generating (positive indicator) or labor consuming (negative indicator).

In financial flow, income is the desirable outcome which is taken as cost-benefit ratio. Further, farm and living expenses need to be considered for accounting the remunerativeness and viability of farming. Since farmers depend on the farm income for their living expenses, riskiness involved in farming can be taken as an indicator for remunerativeness of farming. Finally, crop production is viable only if farmers have enough resources to invest in farming and therefore lower the farming expenses, higher the viability of agriculture. Hence, affordability (seasonal expenses) is very crucial for marginal and small farmers in developing countries and it is taken as an indicator.

Thus the final set of indicators using the framework based on SFD for a holistic evaluation of socio-economic and ecological sustainability includes nutrient efficiency, water use efficiency, employment, cost-benefit ratio, soil pH, soil salinity, soil porosity, biodiversity index, fertilizer impact quotient, pesticide impact quotient, fossil fuel used, affordability, and riskiness.

4. Conclusions and Future Plan

In contrast with the traditional viewpoint of yield as the only indicator for evaluating farming practices, various research groups using different indicator selection frameworks, have proposed several indicator sets for agriculture. The existing frameworks help in identification of indicators but often the process of identification becomes subjective and lacks transparency. Further the selection of indicators is mainly based on criteria like measurability, data availability etc., which affects the process of indicator selection.

In this work, a framework based on systems thinking and stock and flow diagram has been proposed to identify appropriate set of indicators for a holistic evaluation of crop production systems. The process of indicator selection in the proposed framework is systematic and transparent. Each indicator is selected by examining causal flows in the stock and flow diagram of the system.

We have identified a set of thirteen indicators for assessing the viability of agricultural practices with respect to socio-economic and ecological sustainability of crop production system. This will help us in monitoring the state of system as well as the performance of crop production in an effective manner. The information and understandings yielded through these indicators can play an important role in policy decisions, design of agricultural schemes, agricultural extension programs, and budgeting decisions.

Our future plan is to constitute a Delphi panel with various stakeholders including agricultural scientist, economist, ecologist, policy makers, academicians, farmers and develop consensus over the indicators identified. While there has been a constant debate on aggregation of any set of indicators into single indicator which intends to capture the bottom-line and gives a better publicity for the subject, the contenders claim that the arbitrary nature of weighing might disguise serious failings and mislead policy decisions (Sharpe, 2004). So, the justification for any such aggregation will lie on its fitness to the intended purpose and the acceptance of peers (Rosen, 1991). Therefore, a legitimate and reliable methodology needs to be developed for aggregation of the indicator to form a composite index, which can be used as a single indicator of the state of any farming system at field level.

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