

Article

# Ecosystem Network Analysis in a Smallholder Integrated Crop–Livestock System for Coastal Lowland Situation in Tropical Humid Conditions of India

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**Abstract:** The integrated crop–livestock system (ICLS) is a farming strategy that helps to sustain agrobiodiversity, ecosystem services, and restores environmental sustainability. Furthermore, ICLS provides food and nutritional security to the small and marginal farmers in developing nations. In this context a mass-balanced ecosystem model was constructed for a smallholder ICLS along the Indian west coast to analyze the agro-ecological performance in terms of sustainability, resource use, nutrient balance and recycling. Thirteen functional groups were defined in the ICLS model with trophic levels ranging from 1.00 (detritus and benthic nitrogen fixers) to 3.00 (poultry and ruminants). The total system throughput index was estimated to be 1134.9 kg N ha<sup>-1</sup> year<sup>-1</sup> of which 60% was from consumption, 15% from exports, 10% from respiration, and the remaining 15% eventually flowing into detritus. The gross efficiency of the ecosystem was estimated to 0.3, which indicated higher growth rates and low maintenance energy costs. The higher food self-sufficiency ratio of 7.4 indicated the integration of crop–livestock as an imperative system to meet the food and nutritional requirement of the farm family. The indices such as system overhead (60%), Finn’s cycling index (16.6) and mean path length (3.5) denoted that the ICLS is a small, resource-efficient, stable, maturing and sustainable ecosystem in terms of the ecosystem principles and recycling. The present model will serve as the first model on the ICLS from the humid tropics and will help in the evaluation of the other agro-ecological systems using the Ecopath modelling approach. In conclusion, farm intensification through crop and animal diversification has the highest impact on farm productivity, food self-sufficiency and resource-use-efficiency of the smallholder’s livelihood security.

**Keywords:** Ecopath model; ecological group; ecosystem sustainability; nutrient balance; Finn’s cycling index

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## 1. Introduction

Modern intensive agricultural production systems have been affecting ecological sustainability both at the farm and at the regional level [1,2]. Specifically in developing countries, agriculture is becoming more specialized and greatly affecting the synergy between an agroecosystem and the surrounding environment [3]. This practice in turn has been leading to climate change, degradation of natural resources, soil erosion with nutrient leaching and the loss of biodiversity with an increased incidence of pests and diseases [4–6], greatly affecting the livelihoods of small and marginal farmers. These adverse impacts globally imbalance the attainable sustainable harvest of major crops [7]. In this context, agricultural researchers must develop technologies that improve agricultural productivity to ensure food security without compromising the balance of the environment. Hence, these technologies should focus on sustainable intensification, diversification, and the adoption of climate-resilient farming system practices [8,9]. Ecologically sound, climate-resilient and sustainable mixed farming systems are essential to meet the diverse dietary breadth of the global human population [8]. The integrated crop-livestock system (ICLS) is one such farming strategy that helps to sustain agricultural diversity, improves ecosystem services and restores environmental sustainability [10]. The ICLS allows sustainable intensification and diversification of crops and livestock to improve the livelihoods of small and marginal farmers [11]. The balancing of arable crops with livestock could be a possible solution towards sustainable agro-ecology, as the ICLS can limit the negative impacts of agriculture on the environment without compromising the economic benefits of the farming system [12]. Furthermore, Bell et al. [13] described that an ICLS is preferred over monocropping systems due to the efficient use of resources, recycling of nutrients and reduced fluctuations in economic returns.

The knowledge that the operational performance of an ICLS system may be superior to specialized farming would help in justifying the need for ICLSs. The synergistic effects of various trophic interactions between components in the ICLS (crop–animal, crop–poultry, crop–fish and poultry–fish ecological interactions) guide to generate better yields. Many ICLS models have been standardized over a period of time but their application, mapping and analysis have been restricted due to the lack of data on various biotic and abiotic factors. However, an ecological evaluation of ICLS on which crops, dairy, fishery and poultry units are integrated will be beneficial in an agro-ecosystem perspective. In this regard, the Ecopath with Ecosim (EwE) modelling approach provided a framework to model an ecosystem and to assess the quantitative trophic interactions within the ecosystem network [14]. The EwE model works on a combined system of linear equations, which assume the principles of mass balance and mass conservation. The model estimates the various ecosystem performance indicators and network flow indices to evaluate the status and performance of an agro-ecosystem. The model evaluates the extent of integrated nutrient management and recycling, standing biomass and net system production and ecosystem health and stability. The mass-balanced ecosystem model includes various ecological components with balanced component biomass, biomass dynamics, inputs and outputs. In the present study, nitrogen (N) was used as the model currency, which is used as input by smallholder farming systems, because N is a major nutrient and is important in the recycling and pathway analysis of resources in agricultural production systems. Generally, an ICLS is highly productive, which provides a conducive environment for the growth of all ecological groups, which fixes nitrogen. Therefore, modelling such an agroecosystem requires the data on harvests, losses due to runoff and erosion characterizing the pathways of N transfer. Alvarez et al. [15] applied an ecosystem network analysis (ENA) using Ecopath model in ICLS in the highlands of Madagascar and they reported that the intensification of crop–livestock had the highest positive impact on farm productivity, gross margin, food self-sufficiency and environment sustainability. Rufino et al. [16] analyzed the nutrient flow and food self-sufficiency of ICLSs in the highlands of east and southern Africa and highlighted that Ecopath modelling allowed to understand the nature of integration and the diversity of the farming system.

The smallholder ICLSs are highly diverse, heterogeneous and complex in nature, which challenge the use of standard research methodologies in these systems. Moreover, the data collection methods from these agro-systems need to be substantially modified to match with the ambient features of the ICLS. An individual smallholder ICLS could be generally considered as a preferred

standard operational unit for analysis of resource-use efficiency and agricultural sustainability [17,18]. Therefore, the aim of the current study was to apply an ENA to assess the ICLS at whole farm scale. Ecological modelling approach employing the Ecopath with Ecosim (EwE) software was applied in this study to assess a smallholder ICLS in tropical humid conditions situated on India's western coast. The major objective of the research work was to assess the trophic interactions, recycling, resource-use efficiency and the diversity of nitrogen (N) flows and their relation to the system productivity, and to analyze household's food self-sufficiency within the ICLS. We analyzed the productive performance and well-being of the farm's resource base and linked the trophic flows and interactions in the ecosystem. This ecological model will serve as a base for addressing the concept of sustainability and the recycling of resources within an ICLS.

## 2. Material and Methods

### 2.1. Experimental Site and Experimental Details

The present study was undertaken in a smallholder ICLS established at the ICAR (Central Coastal Agricultural Research Institute (Latitude: 15°30'52" N; Longitude: 73°55'01" E), Goa, situated along the western coast of India as a part of the All India Coordinated Research Project on Integrated Farming System, under lowland ecology. The data on different ecological components from the ICLS were gathered from 2015 to 2018. The ICLS covered an area of 0.5 ha including crop components such as rice-cowpea, rice-moong, rice-baby corn and rice-chili. The livestock components in the system were dairy, fishery and poultry. In addition, a small kitchen garden and border plantation of banana, papaya and forage crops were also included in the ICLS (Figure 1). The integrated nutrient management practices were followed in the cropping system to meet the crop nutritional demand. Manure was applied prior to transplanting and incorporated into the soil, and the chemical fertilizer was incorporated as a basal dose during the sowing/planting of the crops [19]. After the crop harvest, the residues were incorporated in situ. The appropriate package of practices was followed as per the crop requirement for rice (*Oryza sativa* L.), cowpea (*Vigna unguiculata* L.), moong (*Vigna radiata* L.), baby corn (*Zea mays* L.) and chili (*Capsicum annuum* L.). Two Milch cross-breed cows were maintained under stall feeding. The cows were fed with green fodder and cattle feed concentrate was given as per the recommendations. A fishpond (250 m<sup>2</sup> area) was constructed at the corner of the field and the poultry unit was raised above the fish pond. To meet the fodder requirement of the ICLS, Napier hybrid bajra (CO-3, CO-4, CO-5, and IGFRI-3 varieties) was planted in an area of 360 m<sup>2</sup> all along the bunds of the field.

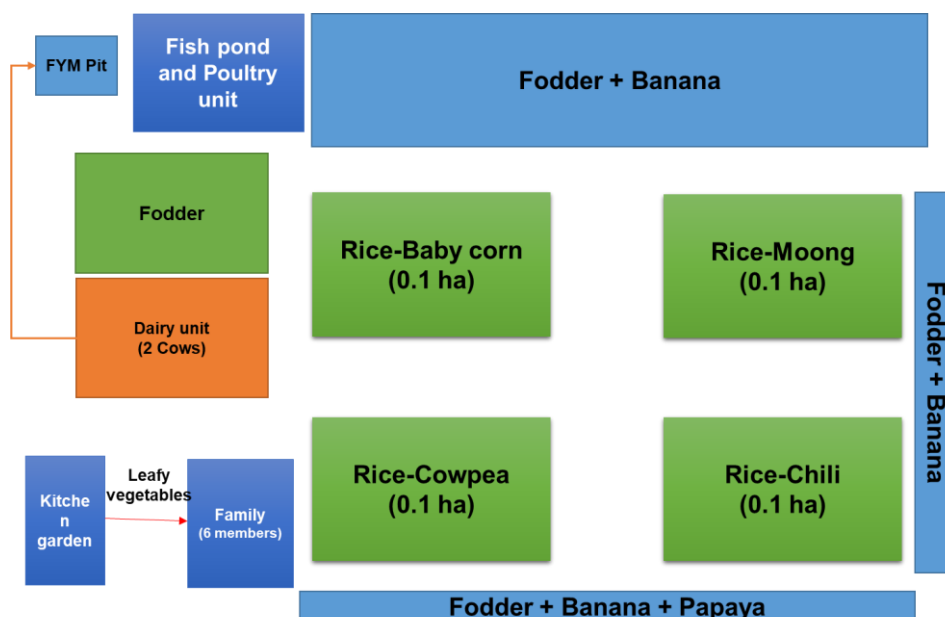


Figure 1. General overview of the integrated crop-livestock system.

## 2.2. Ecopath Data

The field data from various ecological groups were fitted into the Ecopath model. For this, a model currency needed to be identified in terms of energy, biomass or nutrients [20]. In this model, we used N measured in  $\text{kg ha}^{-1}$  as the model currency unit. The N content for various feeds, fertilizers and farm produce were compiled from secondary sources of information [15]. For all the ecological groups, the input data on biomasses (B), production rates (P), consumption rates (Q), harvests (H), exports/losses (E) and diet composition were estimated and applied for the development of the Ecopath model.

## 2.3. Ecological Groups and Input Data

### 2.3.1. Rice (*Oryza sativa* L.)

The rice grain and straw yields recorded were 1855 kg and 2412 kg, respectively, from the ICLS. No rice was cultivated during the winter and summer seasons. N contents of grain and straw were estimated to estimate the total uptake of N in  $\text{kg N ha}^{-1} \text{yr}^{-1}$ . The P and Q values for rice will be similar as the uptake and the yield of N is the same. Due to the sigmoidal growth curve of annual crops, the average biomass (B) would be equal to half of the total plant biomass and hence the value of P/B will be 2.00. Therefore, the input estimates for the rice component were as follows; B: 13.84  $\text{kg N ha}^{-1}$ , P: 27.68  $\text{kg N ha}^{-1}$ , Q: 27.68  $\text{kg N ha}^{-1}$ , H: 35.48  $\text{kg N ha}^{-1}$ , P/B: 2.00, and Q/B: 2.00.

### 2.3.2. Vegetables (Chili and Baby Corn)

The vegetables yield (kg) (cob and stover components) from chili (625, 212), bhendi (200,100), and baby corn (950, 1650) was recorded with a total yield of 3737 kg. The average N harvest index of 0.5 was assumed for the vegetables and hence the total production will be two times the harvest rate. The input estimates for the vegetable component were as follows: B: 0.75  $\text{kg N ha}^{-1}$ , P: 0.30  $\text{kg N ha}^{-1}$ , Q: 0.30  $\text{kg N ha}^{-1}$ , H: 0.15  $\text{kg N ha}^{-1}$ , P/B: 2.00, and Q/B: 2.00.

### 2.3.3. Pulses (Cowpea and Moong)

The cowpea and moong were the components of the group pulses. Cowpea was recorded with a total yield of 120 kg of grains and 455 kg of straw. Similarly, for moong, the grain and straw yields were 65 kg and 280 kg, respectively. After processing the calculations for the input data, the final estimates were as follows: B: 23.56  $\text{kg N ha}^{-1}$ , P: 9.2  $\text{kg N ha}^{-1}$ , Q: 9.2  $\text{kg N ha}^{-1}$ , H: 6.79  $\text{kg N ha}^{-1}$ , P/B: 2.00, and Q/B: 2.00.

### 2.3.4. Weeds and Fodder

The ecological group and weeds included both bund weeds and plot weeds. The common weeds present in the rice production system were *Echinochloa crusgalli* L., *Echinochloa colonum* L., *Ludwigia parviflora* L., *Marselia quadrifolia* L., *Cyperus difformis* L., *Cyperus iria* L., *Fimbristylis milacea* L., vahl, *Eleusine indica* L., *Cynodon dactylon* L. The other common major weeds in chili, baby corn and pulses were *Trianthema portulacastrum* L., *Amaranthus viridis* Linn, *Celosia argentea* L., *Chloris barbata* Sw., *Commelina benghalensis* L., *Cyperus rotundus* L., *Digitaria longiflora* L., *Echinochloa* S.P., *Euphorbia hirta* linn, *Phyllanthus niruri* L., *Trianthema portulacastrum* L., *Portulaca oleracea* linn, *Pennisetum cenchroides* Rich., *Brachiaria reptans* L., *Acalypha indica* L., *Corchorus olitorius* L., *Euphorbia prostrata* L., and *Trianthema portulacastrum* L. For the fodder grown on bunds, the total production (bund length \* planting density) was estimated based on planting density ( $\text{kg m}^{-1}$ ) and bund length. Similarly, for plot weeds, the density ( $\text{kg m}^{-2}$ ) was estimated during the dry season, when the harvest was completed. The input data for the weeds' component were B: 100.4  $\text{kg N ha}^{-1}$ , P: 200.8  $\text{kg N ha}^{-1}$ , Q: 200.8  $\text{kg N ha}^{-1}$ , P/B: 2.00 and Q/B: 2.00 and there was no harvest component for the weeds.

### 2.3.5. Aquatic Weeds

The major aquatic weeds included *Azolla pinnata* R.Br., *Ceratophyllum demersum* L., *Hydrilla verticillata* (L.f.) Royle and *Salvinia molesta* D.Mitch. The total production of the aquatic weeds was calculated by multiplying the density ( $\text{kg m}^{-2}$ ) with the pond area ( $\text{m}^2$ ). The input data for the aquatic weeds were B:  $40.65 \text{ kg N ha}^{-1}$ , P:  $81.3 \text{ kg N ha}^{-1}$ , Q:  $81.3 \text{ kg N ha}^{-1}$ , P/B: 2.00 and Q/B: 2.00 and there was no harvest component for this group.

### 2.3.6. Phytoplankton (Diatoms, Dinoflagellates and Blue Green Algae)

The phytoplankton formed the major producer component in the pond where the fish were grown. The P/B and Q/B for this group was gathered from secondary sources of information [21]. The input data for phytoplankton were B:  $4.8 \text{ kg N ha}^{-1}$ , P/B: 24 and Q/B: 24 and there was no harvest for this ecological component. Production and consumption rates were not estimated for this group.

### 2.3.7. Fruit Crops (Papaya, *Carica papaya* L. and Banana, *Musa acuminata* Colla.)

In this group, there were 40 banana plants and 12 papaya plants. Based on standard methodology, standing stock biomass was estimated for both the fruit crops. The input data for this group were as follows: B:  $50.6 \text{ kg N ha}^{-1}$ , P/B: 0.14 and Q/B: 0.14 and H:  $0.16 \text{ kg N ha}^{-1}$ .

### 2.3.8. Trees (Mango, *Mangifera indica* L.)

For this group, the input data were as follows: B:  $10.6 \text{ kg N ha}^{-1}$ , P/B: 0.55 and Q/B: 0.55 and H:  $2.86 \text{ kg N ha}^{-1}$ .

### 2.3.9. Ruminants (2 Cross-Bred Cows)

Biomass and production estimates for the ruminants were calculated using the standard method proposed by Dalsgaard et al. [22]. The final estimates of the input data for the ecological group were as follows: B:  $8.70 \text{ kg N ha}^{-1}$ , P/B: 2.26 and Q/B: 27.8 and H:  $8.32 \text{ kg N ha}^{-1}$ . Being a consumer group, the diet composition was also entered as input data for this group, which included 80% fodder, 10% rice, 1% pulses and 9% from imported off-farm feed.

### 2.3.10. Poultry

In this group, the harvests of eggs and meat were considered separately. The diet for the group was from on-farm and off-farm sources. The final estimates of the input data for poultry were as follows: B:  $2.32 \text{ kg N ha}^{-1}$ , P/B: 4.20 and Q/B: 304.4 and H:  $7.36 \text{ kg N ha}^{-1}$ . The diet composition of the group included 80% imports, 10% rice and 10% from aquatic weeds.

### 2.3.11. Fish (Rohu (*Labeo rohita*, F. Hamilton), Catla (*Catla catla*, F. Hamilton) and Common carp (*Cyprinus carpio*, L.) at 50:25:25 Ratio)

In this group, 250 fingerlings (each fingerling with 4 g mean weight) of the three species, Rohu, Catla and Common carp were stocked at the ratio of 50:25:25 in the  $250 \text{ m}^2$  pond. Therefore, the total biomass at the time of stocking was 1 kg. The final estimates of the input data for the fish group were as follows: B:  $2.38 \text{ kg N ha}^{-1}$ , P/B: 1.95 and Q/B: 15.2 and H:  $4.62 \text{ kg N ha}^{-1}$ . Phytoplankton (75%), detritus (20%) and aquatic weeds (5%) were the major source of diet for fishes.

### 2.3.12. Detritus and Benthic Nitrogen Fixers (BNF)

Soil detritus and BNF were the essential components of the ecosystem model, which formed the source of all primary producers and the plants and these components determined the health of the ecosystem model. Soils were sampled and analyzed thrice during the monitoring period in order to get a good picture of the soil conditions and possible changes. Soil samples were subjected (0.15 m soil depth) for chemical analysis, including pH, N, phosphorus (P), potassium (K,) and organic carbon content using standard protocols. For BNF, the input estimates were B:  $5.6 \text{ kg N ha}^{-1}$ , P/B: 34 and

there were no Q/B and harvest components for this group as the base trophic groups. For detritus, the input estimate was only for biomass, B: 1800 kg N ha<sup>-1</sup>.

#### 2.4. Ecosystem Modelling of Lowland Integrated Crop–Livestock System (ICLS)

An Ecopath model was constructed for the ICLS with an area of 0.5 ha employing the software Ecopath with Ecosim (EwE) (Version 6.5) [14]. The Ecopath model characterized the balance between biomass gains through production and losses. There were two master equations in the model, one to describe the mass balance and one for the energy balance of each functional group. The energy balance of each ecological group in the system was represented as: consumption (Qi) = production (Pi) + respiration (Ri) + unassimilated food (Ui), which describes the energy input (Qi) and energy output (Pi, Ri and Ui) of all the living groups in the model to be balanced. Twelve ecological groups were considered as the functional groups for developing the model. The groups identified were pulses, rice, vegetables, field weeds, fodder, aquatic weeds, phytoplankton, fruit trees, multi-purpose tree, poultry, ruminants, fish, BNF and detritus. Similar ecological grouping was considered for constructing the ecosystem models in different agroecosystems in earlier reports. [23]. In mass-balanced trophic models, the pedigree of input data is a coded statement classifying the origin of input data (i.e., the type of data on which it is based), and similarly, specifying the likely uncertainty associated with the input. For this, the key criterion used was that the primary data of an input parameter was calculated from the modelled ecosystem using empirical equations. Furthermore, the pedigree index values were used to calculate an overall pedigree index for the mass-balance model. The index values for input data ranged from a value of 0 (for non-local data) to 1 (for local data). In this study, all the input parameters for all the ecological groups were considered from local data. In order to construct a mass-balanced model for an ecosystem, at least four of the basic input parameters (1. biomass (B), 2. production/biomass (P/B), 3. consumption/biomass (Q/B), and 4. diet composition) should be made available for the functional groups. Thus, the model can estimate the unknown basic input parameter and generally, 'EE' is kept as the unknown parameter. Apart from these parameters, N harvest data (Table 1) were also provided as an input for the model. The biomass for various ecological groups was estimated using the methodology given by Dalsgaard and Official [24]. The biomass, production/biomass, consumption/biomass and harvest rates for various ecological groups were calculated as kg N ha<sup>-1</sup> year<sup>-1</sup>. The diet composition matrix was prepared for the ecological groups based on their on-farm and off-farm feed consumption data (Table 2). With all these inputs, the model was balanced using EwE and the key criterion for mass balancing was that EE<sub>i</sub> should lie between 0 and 1. In addition, the values of P/Q were also checked for all the consumer groups (ruminants, poultry and fish) to ensure that this index ranged from 0.1 to 0.3 for the majority of the functional groups.

**Table 1.** Harvest data for the various ecological groups.

	<b>Group Name</b>	<b>Value (kg N ha<sup>-1</sup> year<sup>-1</sup>)</b>
1	Pulses	6.79
2	Rice	20.42
3	Vegetables	0.75
4	Weeds	0
5	Aquatic weeds	5.5
6	Phytoplankton	0
7	Fruit crops	0.16
8	Trees	2.86
9	Poultry	7.36
10	Ruminants	8.32
11	Fish	4.62
12	Benthic Nitrogen Fixers	0
13	Detritus	0
14	Sum	56.18

### 2.5. Trophic Relationships in the Model

To represent the trophic relationships in the model, the diet matrix was the major input data that corresponded to flows linking various ecological groups and identifying the prey–predator interactions in the ecosystem. The diet matrix provided flows from preys to predators [25]. The food composition of a predator ( $DC_{ji}$ ) was the fraction (in weight) of each prey ( $i$ ) in the stomach of the predator ( $j$ ). The diet composition for various consumer groups such as ruminants, poultry and fish were defined based on the on-farm and off-farm feed inputs in the agroecosystem (see the section ‘Ecological groups and input data’). For the eight producer groups (pulses to trees), the diet composition was defined as proportions of BNF and detritus (Table 2).

**Table 2.** Final diet matrix for the integrated crop–livestock system (ICLS) model.

Prey\Predator	1	2	3	4	5	6	7	8	9	10	11
1 Pulses	0	0	0	0	0	0	0	0	0	0.01	0
2 Rice	0	0	0	0	0	0	0	0	0.1	0.1	0
3 Vegetables	0	0	0	0	0	0	0	0	0	0	0
4 Weeds	0	0	0	0	0	0	0	0	0	0.8	0
5 Aquatic weeds	0	0	0	0	0	0	0	0	0.1	0	0.05
6 Phytoplankton	0	0	0	0	0	0	0	0	0	0	0.75
7 Fruit crops	0	0	0	0	0	0	0	0	0	0	0
8 Trees	0	0	0	0	0	0	0	0	0	0	0
9 Poultry	0	0	0	0	0	0	0	0	0	0	0
10 Ruminants	0	0	0	0	0	0	0	0	0	0	0
11 Fish	0	0	0	0	0	0	0	0	0	0	0
12 Benthic Nitrogen Fixers	0.5	0	0.4	0.2	0.2	0.1	0.2	0.5	0	0	0
13 Detritus	0.5	1	0.6	0.8	0.8	0.9	0.8	0.5	0	0	0.2
14 Import	0	0	0	0	0	0	0	0	0.8	0.09	0
15 Sum	1	1	1	1	1	1	0	1	1	1	1

### 2.6. Balancing the Model and Pedigree Index

The mass balancing of the ICLS was carried out using the Ecopath modelling software (EwE) and rational modifications were incorporated in the input data to balance the model [14,26] with the agroecosystem background and plausible reasoning, rather than the statistical equations behind the EwE. The biomass and diet compositions of few ICLS components/groups were marginally modified to get the mass-balance model. The validity of the input data was analyzed using the Ecopath pedigree index [27,28]. The key criterion used here was that the input estimated from the primary data as a rule were better than data from elsewhere [14]. In this model, the majority of the input data were collected from the primary sources and only a few were estimated from secondary sources of information [22].

Based on the individual pedigree values, an overall ‘pedigree index’  $P$  is calculated based on:

$$P = \frac{\sum_{i=1}^n \sum_{j=1}^n l_{ij}}{n}$$

where  $l_{ij}$  is the pedigree index ( $P$ ) for an individual group, and parameter ‘ $j$ ’ and ‘ $n$ ’ is the total number of functional groups. A measure of fit, ‘ $t^*$ ’ was also estimated for the pedigree index:

$$t^* = P * \frac{\sqrt{N-2}}{\sqrt{1-P^2}}$$

### 2.7. Ecosystem Statistics and Network Indices

The mass-balanced ecosystem model yields a network flow diagram and different ecological elements that represent various features of the ecosystem (Table 3). To assess the ecological structure of the ICLS, indices such as the total system throughput (TST), gross efficiency (GE), net primary production (NPP), total primary production/biomass (PP/B), total biomass/TST (TB/TST), mean trophic level of the functional groups, Shannon index and the system omnivory Index (SOI) were used [14]. The mass-balanced model generated a trophic flow diagram, which represented all the flows and biomasses in the ecosystem. In an ecosystem, the maturity and stability are the factors that determine the system functioning [29]. The Ecopath model gives several indicators to evaluate ecosystem maturity and stability [14]. The SOI is an important index, which corresponds to the maturity of the ecosystem [29]. SOI described how the prey–predator interactions were arranged between trophic levels. Finn’s cycling index (FCI) provided the amount of material or energy which was recycled within the ecosystem [16]. The mean path length (MPL) can be calculated, which describes how many times a unit of energy is transferred between ecological groups in the ecosystem. The ascendancy index (A) measures the extent of the food web balance in an ecosystem. System overhead (SO) estimates the energy balance of an ecosystem and it is in contrast to ascendancy. A and SO were used as indices to determine the ecosystem’s maturity and stability.

In an ecosystem, all the functional components are significant and each group plays a different role towards the ecosystem functioning. However, the presence of certain groups is crucial for keeping the integrity and stability of the system. These groups/species are called keystone species [20]. The keystone species index (KSI) was used to identify the important functional groups that significantly affected the trophic interactions in an ecosystem. For this, the overall impact was plotted against the KSI to identify keystone groups (groups, which play a significant role in the food web with relatively low biomass) and dominant groups (groups which are important in the food web with large relative biomass) in the ecosystem. The indicators are computed by the following equations below [30,31].

Total system throughput (TST):

$$TST = \sum_{ij} T_{ij}$$

where  $T_{ij}$  is the flow from compartment  $i$  to compartment  $j$ .

Ascendancy (A):

$$A = \sum_{ij} T_{ij} \log \left( \frac{T_{ij} T}{T_i T_j} \right)$$

System overhead (SO):

$$SO = \sum_{i=1}^n \sum_{j=1}^n (T_{ij}) \log \left( \frac{T_{ij}^2}{\sum_{j=1}^n T_{ij} \sum_{i=1}^n T_{ij}} \right)$$

Finn’s cycling index:

$$FCI = \frac{TST}{TST_c}$$

where  $TST_c$  represents the amount of TST that is recycled within the system, ratio of ascendancy (A) and developmental capacity (C).



**Table 3.** Performance indicators used for the comparison of ecosystems.

Performance Indicator	Definition	Significance
Functional group (FG)	A group of single species, individuals of same size/age or ecologically related species	The number and type of functional groups determines the diversity of the ecosystem
Sum of all consumption (t km <sup>-2</sup> year <sup>-1</sup> ) (SC)	Total consumption within the ecosystem	Structure of the ecosystem
Sum of all exports (t km <sup>-2</sup> year <sup>-1</sup> ) (SE)	Total exports from the ecosystem	Structure of the ecosystem
Sum of all flows into detritus (t km <sup>-2</sup> year <sup>-1</sup> ) (SD)	Total flows to detritus within the ecosystem	Structure of the ecosystem
Sum of all production (t km <sup>-2</sup> year <sup>-1</sup> ) (SP)	Summation of all production within the ecosystem	Structure of the ecosystem
Total system throughput ((t km <sup>-2</sup> year <sup>-1</sup> ) (TST)	Summation of all trophic flows (total consumption + total export + total respiration + total flows to detritus) in the ecosystem	Provides an idea about the size of the ecosystem
Mean trophic level of the ecosystem (MTL)	Weighted mean value of all trophic levels in the ecosystem	Gives the overall picture of the trophic network in the ecosystem
Gross efficiency (GE)	Ratio between the total harvests and NPP in the ecosystem	Represents the harvest of groups in an ecosystem with respect to inputs
Net system production (t km <sup>-2</sup> year <sup>-1</sup> ) (NSP)	This is the difference between total primary production and total respiration	Maturity of the ecosystem, it will be high in immature ecosystems and close to zero in mature ones
Total biomass (exc. detritus) (t km <sup>-2</sup> year <sup>-1</sup> ) (B)	Total biomass of all functional groups except detritus	Gives the carrying capacity within the ecosystem
Total primary production/B (P/B)	Ratio between total primary production and total biomass in the ecosystem	Maturity of the ecosystem, in mature ecosystems, the ratio will be low
Total primary production/respiration (PP/R)	Ratio between total primary production and total respiration in the ecosystem	Maturity of the ecosystem, this index demonstrates values greater than unity in immature ecosystems
Total biomass/TST (TB/TST)	Ratio between total biomass and TST	Maturity of the ecosystem, maximum values (close to 1) will be observed for mature ecosystems
System omnivory index (SOI)	Average omnivory indices of all consumers weighted by the logarithm of each consumer's food intake	Maturity of the ecosystem, it yields higher values in mature ecosystems (>0.5)
Mean path length (MPL)	Average ecological distance between various pathways in the food web	Maturity of the ecosystem, higher values denote maturity of ecosystems
Finn's cycling index (FCI)	The recycled fraction of the ecosystem's TST	Maturity and stability of the ecosystem, higher values show more mature and resilient ecosystems
Ascendency (%) (A)	This measures the extent of balance of food web in an ecosystem. It is in contrast to system overhead	Maturity of the ecosystem, higher values for this index indicate maturity of the system (>50%)
System overhead (%) (SO)	Energy in balance for an ecosystem. It is contrast to ascendency	Stability of the ecosystem, in stable and resilient ecosystems, the value will be high (>50%)
Ecopath pedigree index (PI)	The pedigree of input data showing the origin of an input data	This index provides the extent of validity of the model based on the input data. If the model is based on local data, the index will be more than 0.6

### 3. Results

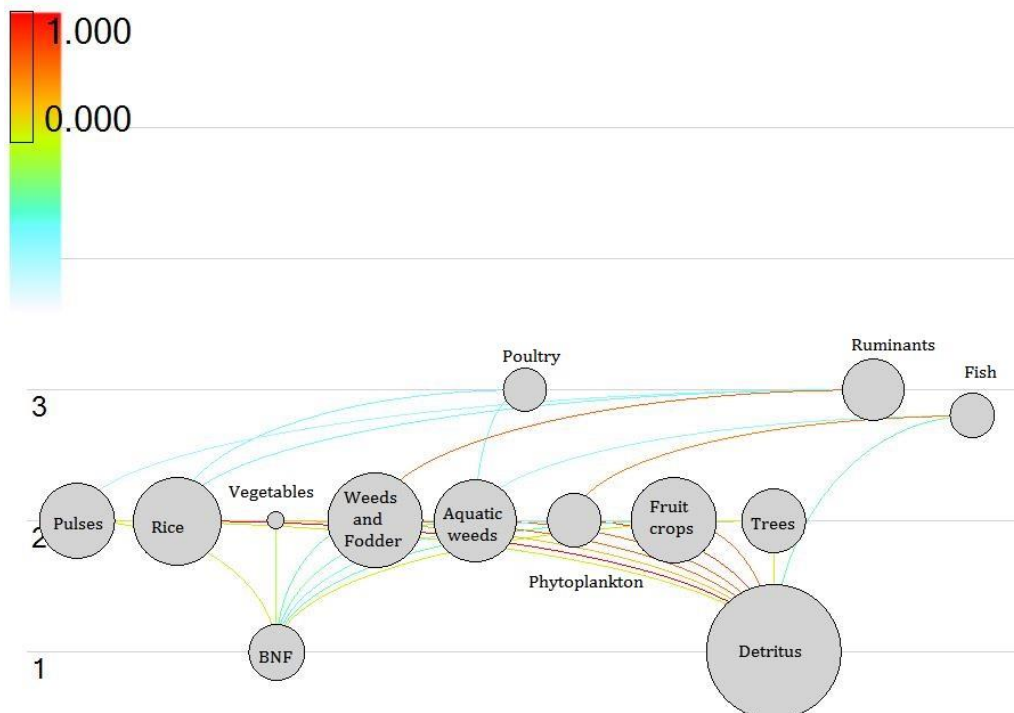
#### 3.1. Mass-Balanced Model and Ecological Structure

In this study, the quality of data was assured, as the majority of the data were sourced from the ecosystem itself. The validity of the data used and the reliability and dependability of the model were tested using the Ecopath pedigree index. The Ecopath pedigree index yielded a very high value of 0.84 showing the high quality of data with a measure of fit, 5.3, and indicated the importance of primary data in Ecopath modelling. The P/Q ratios ranged from 0.01 to 1, meeting the requirements

of a balanced ecosystem model. The input values and output estimates for the mass-balanced model are summarized in Table 4. The producer groups shared the majority of the ecosystem biomass excluding detritus and BNF. The major consumer groups, ruminants (8.70), poultry (2.32) and fish (2.38) presented the lowest biomass estimates. The trophic network clearly indicated that the majority of the trophic flows accumulated at the base of the trophic network (Figure 2). There were two major paths (from BNF and detritus) in the ecosystem and trophic flows from detritus and BNF together contributed to about 80% of the total flows. Most of the activities in terms of flow accumulated at the base of the trophic food web where BNF and phytoplankton were the main food sources. Similarly, the BNF-based pathway was channeled through major producer groups to consumers in the system (Figure 2). The highest trophic levels or the top predators in the ecosystem were poultry, ruminants and fish.

**Table 4.** Basic parameters of the mass-balanced trophic model for the ICLS. TL: trophic level, B: biomass (kg N ha<sup>-1</sup> year<sup>-1</sup>), P/B: production/biomass (year<sup>-1</sup>), Q/B: consumption/biomass (year<sup>-1</sup>), EE: ecotrophic efficiency, P/Q: production/consumption or gross efficiency of food conversion (year<sup>-1</sup>).

	Group Name	Trophic Level	Biomass (kg N ha <sup>-1</sup> year <sup>-1</sup> )	P/B	Q/B	EE	P/Q
1	Pulses	2	23.56	2	2	0.20	1.00
2	Rice	2	60.1	2	2	0.96	1.00
3	Vegetables	2	0.75	2	2	0.34	1.00
4	Weeds and fodder	2	100.4	2	2	0.96	1.00
5	Aquatic weeds	2	40.65	2	2	0.96	1.00
6	Phytoplankton	2	4.8	24	24	0.24	1.00
7	Fruit crops	1	50.6	0.14	0.14	0.62	1.00
8	Trees	2	10.6	0.55	0.55	0.39	1.00
9	Poultry	3	2.32	4.2	304.4	0.72	0.01
10	Ruminants	3	8.704	2.26	27.8	0.17	0.08
11	Fish	2.8	2.38	1.95	15.2	0.99	0.13
12	BNF	1	5.6	34	0	0.50	
13	Detritus	1	1800				



**Figure 2.** The trophic structure of the ICLS depicting the trophic levels and flows in the ecosystem, the size of the nodes is according to their biomass and the color of the nodes is based on the quantity of material flow respectively ( $\text{kg N ha}^{-1} \text{ year}^{-1}$ ). Trophic levels are displayed in the Y axis.

### 3.2. Ecotrophic Efficiency

The value of EE should be less than 1 for the mass balancing and the range indicates that the N input to the specific ecological group is less than the output. In an ecosystem model, certain functional groups will exhibit higher values for EE ( $>0.7$ ) and others will demonstrate lower levels of EE ( $<0.5$ ). In the current study, EE was very high for fish (0.99), weeds and fodder (0.96), rice (0.96), aquatic weeds (0.96) and poultry (0.72) whereas, ruminants (0.17), pulses (0.2), phytoplankton and vegetables demonstrated the lowest values of EE (Table 4). The EE value for detritus was observed to be 0.49 and it was much less than the index upper limit (1.00).

### 3.3. Gross Efficiency (GE)

The GE value indicates the weighted average efficiency (for consumption and production) for all the environmental groups in the system and it varies between 0 to 1. For the agroecosystem model developed in this study, the value was observed to be 0.3, it indicated higher growth rates and low energy maintenance costs.

### 3.4. Ecosystem Properties and Network Indices

Ecosystem and network flow indices for the ICLS system are described in Table 5. The value of the Shannon diversity index for the ICLS was 2.52. The TST of the system was estimated as  $1134.9 \text{ kg N ha}^{-1} \text{ year}^{-1}$  of which 60% was from consumption, 15% from exports, 10% from respiration and 15% eventually flowing into detritus. The total net primary production index was 17% of the TST ( $190.4 \text{ kg N ha}^{-1} \text{ year}^{-1}$ ). The PP/B index was extremely low (0.61) and the value for TB/TST was comparatively high (0.27). These indices explained that the ICLS has higher rates of maturity, recycling and stability. The value of ascendancy and SO was 40% and 60%, respectively, for the ICLS system. The ecosystem indicators such as TST, GE, NPP and the mean trophic level were found to be moderate and the SOI was low when considering the area spread (0.5 ha). The SOI (0.09) was relatively low as the ecosystem components were specialist feeders. The greater dimensions for FCI (16.6) and the MPL (3.50) indicated the higher rates of recycling in the ICLS (Table 5) and also suggested that the ICLS has the strength in reserve to resist and recover from unexpected disturbances in the ecosystem and able to withstand under adverse environmental conditions. Therefore, the ICLS ecosystem was relatively stable and sustainable, with higher rates of recycling within the system.

**Table 5.** Ecosystem and network flow indices.

Parameter	Value
Sum of all consumption ( $\text{kg N ha}^{-1} \text{ year}^{-1}$ )	1562.33
Sum of all exports ( $\text{kg N ha}^{-1} \text{ year}^{-1}$ )	-427.35
Total system throughput ( $\text{kg N ha}^{-1} \text{ year}^{-1}$ ) (TST)	1134.98
Sum of all production ( $\text{kg N ha}^{-1} \text{ year}^{-1}$ )	802.43
Mean trophic level of the functional groups	2.34
Gross efficiency (harvest/net p.p.) (GE)	0.30
Calculated total net primary production ( $\text{kg N ha}^{-1} \text{ year}^{-1}$ ) (NPP)	190.40
Total primary production/total biomass (PP/B)	0.61
Total biomass/total system throughput (TB/TST)	0.27
Total biomass (excluding detritus)	309.93
Total harvest ( $\text{kg N ha}^{-1} \text{ year}^{-1}$ )	56.18
System omnivory index (SOI)	0.09
Finn's cycling index	16.60

Mean path length	3.50
Ascendency (%) (A)	40.40
System overhead (%) (SO)	59.60
Food self-sufficiency ratio	7.64
Ecopath pedigree index	0.84
Measure of fit, $t^*$	5.31
Shannon diversity	2.52

### 3.5. Mean Trophic Level and Keystone Groups

The mean trophic level of the ICLS was found to be 2.34 (Table 5). Based on the KSI, the most important functional groups in the ecosystem were poultry (1), ruminants (0.599), fish (0.602), rice (0.673) and BNF (0.644) (Table 6). These groups were considered to be efficient carriers of energy transfer in the ecosystem linking other trophic groups.

**Table 6.** Keystone species index and the relative total impact.

	Group Name	Keystone Index	Keystone Index #2	Relative Total Impact
1	Pulses	-0.48	0.66	0.39
2	Rice	-0.31	0.49	0.67
3	Vegetables	-2.27	0.87	0.0059
4	Weeds	-0.44	0.21	0.59
5	Aquatic weeds	-0.64	0.29	0.29
6	Phytoplankton	-0.38	1.42	0.46
7	Fruit crops	-2.35	-1.48	0.006
8	Trees	-1.01	0.46	0.11
9	Poultry	-0.053	2.07	1.00
10	Ruminants	-0.28	1.27	0.59
11	Fish	-0.27	1.84	0.60
12	BNF	-0.24	1.50	0.64

## 4. Discussion

### 4.1. Ecosystem Features and Organization

The features of an ecosystem such as trophic organization, stability, resource-use efficiency and sustainability with material and energy flows can be assessed by the ecosystem-modelling approach using the Ecopath software. In this study, for the first time in India, an ecosystem model was constructed for a small-scale ICLS using the standard methodology followed in earlier studies [14,22]. There are only a few reports available on developing the ecosystem-based models for ICLS [24]. The model was developed based on local data as far as possible and hence, the Ecopath pedigree index and the associated measure of fit ' $t$ ' indicated a better pedigree for the model. The model also highlighted the further data requirements on microbial biomass to strengthen the trophic structure and network analysis in the ICLS. The bacterial biomass components were included in the detritus and BNF groups as per the standard Ecopath modelling guidelines [21].

The ecosystem performance indicators and network indices identified in this study were useful for analyzing and comparing the status and efficiency of agro-ecological systems. The modelling of the ICLS indicated that the integration of various components in an ICLS can generate productive, efficient, highly stable and sustainable farming systems compared to the monoculture systems [16,32]. Twelve ecological groups were identified in the ICLS system with a total biomass of 2109.9 kg N ha<sup>-1</sup> year<sup>-1</sup>. The total biomass excluding detritus was found to be 309.93 kg N ha<sup>-1</sup> year<sup>-1</sup> and the value was higher compared to the values obtained in models constructed for ICLS units elsewhere [22]. The trophic levels ranged from one (BNF and detritus) to three (poultry and ruminants). The keystone functional groups in the ecosystem were poultry, ruminants, rice, BNF, and fish.

The total system throughput is defined as the summation of consumption, imports, exports, flows to detritus, harvests and exports and the index represents the size of the ecosystem in terms of the flow network [31]. The TST of the ICLS recorded was 1134.98 kg N ha<sup>-1</sup> year<sup>-1</sup>, which was comparatively higher than earlier [15,16]. The value was relatively high due to the small size of the ecosystem and the associated recycling within the components, especially the fodder and organic residue recycling. In our study, N recycled within the system was 16.6%, whereas it ranged from 0.9% to 11% on the African [16] and 2.5% to 4.4% in the Madagascan ecosystems [15]. The health and sustainability of the agricultural systems are associated with the diversity that the systems hold within it [33]. The agricultural diversity is counted in terms of the number of groups present in the system and the individual abundance of each group. To represent agricultural diversity in farming systems, the Shannon index is used as the measure of diversity, which is computed by weighing each group of organisms in the model by its abundance as expressed in terms of average biomass expressed in kg N ha<sup>-1</sup>. The value of the index for the ICLS in this study was 2.52, indicating a higher diversity compared to the ecosystem models developed for the other farming systems [22]. The food self-sufficiency ratio (FSSR) for the ICLS was 7.64, designating that the system was adequately self-sufficient to cater to the energy and protein needs of the farm family. The cereals, pulses, vegetables, milk, eggs and fish provided important sources of nutrition and only the excess produce was sold in the market. The study also indicated that with increases in the N consumption, the sum of all productions and food self-sufficiency improved significantly. The present ICLS system consumed more within the ecosystem and directly contributed to the food production, and this also indicated the better management of manure produced in the system, demonstrating the potential of ICLS in N recycling [16].

#### 4.2. Ecosystem Performance Indicators

The ecosystem performance of an ICLS can be quantified through the ecosystem and network flow indices obtained in the Ecopath model. The ecosystem stability and sustainability depend on the performance of various ecological groups and the amount of recycling within the system. The SOI is generally considered as an index to represent the maturity and stability of the ecosystem. However, the former index cannot be considered as an index in this system, as the system is small, and the groups are specialist feeders with high rates of recycling within the system (FCI = 16.6). The next proxy to assess the maturity and stability of an ecosystem is the SO which computes the available optional pathways along which biomass may exchange between the ecological groups [34]. The former index is also identified as a measure to evaluate the resistance of the ecosystem to external perturbations. The SO follows a positive correlation with the maturity and stability of the ecosystem, and more specifically indicates the ecological sustainability of the ICLS. In this ICLS model, the higher values for the SO indicated that the system was more stable and sustainable and developing more towards a mature ecosystem. Ascendency is another important index, which determines the ecosystem's growth and development, and quantifies the diversity and the ecosystem network [35]. The ascendency values determined using Ecopath model were inversely correlated to the ecosystem concept of sustainability. The additional estimates such as PP/B and TB/TST also determined the stability and maturity of the ecosystem. The PP/B index was extremely low (0.61), resembling an ecosystem with high rates of recycling and stability. Similarly, a higher value for TB/TST represents the ICLS as an ecosystem with higher levels of maturity and stability. The FCI and MPL are indicators of the resource-use efficiency, recycling, maturity and stability of the ecosystem. The present ICLS model recorded higher FCI and MPL values of 16.6 and 3.5, respectively. Greater values of these indices in the ICLS model showed that there was a higher degree of recycling in the system and thus, the ecosystem was efficient in resource use, and was sustainable and stable in nature. The metadata on Ecopath models show that the values of FCI and MPL range from 0.19 to 24.8 and 1.7 to 4.5, respectively [36]. Torres et al. [37] opined that the FCI and MPL are expected to increase with the sustainability of an ecosystem.

#### 4.3. Nutrient Balances in the Integrated Crop-Livestock System (ICLS)

The balance of trophic flows through the ICLS model is another important ecosystem performance indicator [38]. There should be an adequate balance between the input and output components in the agroecosystem to sustain the system in the long run. This ICLS model showed that the recycling of crop residues, integrating multiple components at different trophic levels, cultivation of plants capable of fixing N, the inclusion of the fish component, poultry and dairy were intended to increase the farm-use efficiency [32]. These modifications in integration will yield enhanced ecological performance and sustainability as explained by the aforementioned sustainability indicators and cycling indices. Moreover, the imports of fertilizers and feed were minimized in the ICLS model using crop residues, weeds, fodder crops, phytoplankton and aquatic weeds. The gross efficiency of the ecosystem represented an indirect measure of the balances in the agro-ecological systems and the index was measured as the ratio of the total output (harvests) to the total net primary production in the system. The index provided the weighted average efficiency (for consumption and production) for all the ecological components in the system. In this model, the GE index yielded higher growth rates, resource use and low maintenance energy costs. Hence, the GE values were comparable with the values obtained for ICLS models and it was substantially greater than the values obtained for monocrop systems in lowland agricultural systems [22,39]. The amount of import in this ICLS model was also found to be significantly lower compared to mono-cropping systems as reported by [22].

This ICLS model can be applied for similar climatic conditions on the west coast of India involving functional groups such as crops, livestock, fish, and poultry. The major uncertainty associated with these modelling exercises are the quality and quantity of local data that need to be considered during the development of the ICLS. Subsequently, it would be challenging to find a balance between the productivity, adaptability and the stability of the ICLS, which require an improved package of practices focused on resource-use efficiency and recycling. Furthermore, the ecosystem network analysis indicators could be complemented with farm-scale modelling approaches to assess the system performance indicators such as food production, income and employment opportunities in the long run.

## 5. Conclusions

In this study, we developed an ecosystem model for monitoring and assessing the integrated crop–livestock system to generate appropriate agro-ecological performance indicators. We used the input data in terms of the ecosystem context such as biomass, production, consumption, ecotrophic efficiency, harvest and diet components. These input parameters were used to generate ecosystem performance indicators such as the total flows in the system, gross efficiency, maturity, stability and sustainability and the recycling of inputs and outputs. The model indicated a higher level of food self-sufficiency (7.64), indicating a reliance on the model with a higher FCI (16.60), which showed higher recycling and resource-use efficiency. The gross efficiency of 0.3 denoted higher growth rates and low maintenance energy costs. The comprehensive analysis using the Ecopath model indicated that the ICLS model is a small, resource-efficient, stable, maturing and sustainable ecosystem in terms of the ecosystem principles and the recycling and nutrient balance in the system is far ahead of the monocropping systems.

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## References

1. Tilman, D.; Cassman, K.G.; Matson, P.A.; Naylor, R.; Polasky, S. Agricultural sustainability and intensive production practices. *Nature* **2002**, *418*, 671–677.
2. Cano, E.; Cano-Ortiz, A.; Musarella, C.M.; Piñar Fuentes, J.C.; Ighbareyeh, J.M.H.; Leyva Gea, F.; del Río, S. Mitigating Climate Change Through Bioclimatic Applications and Cultivation Techniques in Agriculture (Andalusia, Spain). In *Sustainable Agriculture, Forest and Environmental Management*; Springer: Singapore, 2019; pp. 31–69.
3. Lemaire, G.; Franzluebbers, A.; Carvalho, P.C. de F.; Dedieu, B. Integrated crop–livestock systems: Strategies to achieve synergy between agricultural production and environmental quality. *Agric. Ecosyst. Environ.* **2014**, *190*, 4–8.
4. Paramesh, V.; Arunachalam, V.; Nikkhah, A.; Das, B.; Ghnimi, S. Optimization of energy consumption and environmental impacts of arecanut production through coupled data envelopment analysis and life cycle assessment. *J. Clean. Prod.* **2018**, *203*, 674–684.
5. Place, S.E.; Mitloehner, F.M. Invited review: Contemporary environmental issues: A review of the dairy industry’s role in climate change and air quality and the potential of mitigation through improved production efficiency. *J. Dairy Sci.* **2010**, *93*, 3407–3416.
6. Franzluebbers, A.J.; Stuedemann, J.A. Early response of soil organic fractions to tillage and integrated crop–livestock production. *Soil Sci. Soc. Am. J.* **2008**, *72*, 613–625.
7. Moritz, C.; Agudo, R. The future of species under climate change: Resilience or decline? *Science* **2013**, *341*, 504–508.
8. Martin, G.; Moraine, M.; Ryschawy, J.; Magne, M.-A.; Asai, M.; Sarthou, J.-P.; Duru, M.; Therond, O. Crop–livestock integration beyond the farm level: A review. *Agron. Sustain. Dev.* **2016**, *36*, 53.
9. Paramesh, V.; Arunachalam, V.; Nath, A.J. Enhancing ecosystem services and energy use efficiency under organic and conventional nutrient management system to a sustainable arecanut based cropping system. *Energy* **2019**, *187*, 115902.
10. Magdoff, F. Ecological agriculture: Principles, practices, and constraints. *Renew. Agric. Food Syst.* **2007**, *22*, 109–117.
11. Manjunath, B.L.; Paramesh, V.; Mahajan, G.R.; Reddy, K.V.; Das, B.; Singh, N.P. A Five Years Study on the Selection of Rice Based Cropping Systems in Goa, for West Coast Region of India. *J. Environ. Biol.* **2018**, *39*, 393–399.
12. Dumont, B.; Fortun-Lamothe, L.; Jouven, M.; Thomas, M.; Tichit, M. Prospects from agroecology and industrial ecology for animal production in the 21st century. *Animal* **2013**, *7*, 1028–1043.
13. Bell, L.W.; Moore, A.D. Integrated crop–livestock systems in Australian agriculture: Trends, drivers and implications. *Agric. Syst.* **2012**, *111*, 1–12.
14. Christensen, P.; Boelling, D.; Pedersen, K.M.; Korsgaard, I.R.; Jensen, J. Relationship between sperm viability as determined by flow cytometry and nonreturn rate of dairy bulls. *J. Androl.* **2005**, *26*, 98–106.
15. Alvarez, S.; Rufino, M.C.; Vayssières, J.; Salgado, P.; Tiftonell, P.; Tillard, E.; Bocquier, F. Whole-farm nitrogen cycling and intensification of crop–livestock systems in the highlands of Madagascar: An application of network analysis. *Agric. Syst.* **2014**, *126*, 25–37.
16. Rufino, M.C.; Tiftonell, P.; Reidsma, P.; López-Ridaura, S.; Hengsdijk, H.; Giller, K.E.; Verhagen, A. Network analysis of N flows and food self-sufficiency—A comparative study of crop–livestock systems of the highlands of East and southern Africa. *Nutr. Cycl. Agroecosystems* **2009**, *85*, 169–186.
17. Mukhlis; Melinda, N.; Nofialdi; Mahdi. The Integrated Farming System of Crop and Livestock: A Review of Rice and Cattle Integration Farming. *Int. J. Sci. Basic Appl. Res.* **2018**, *42*, 68–82.
18. Salton, J.C.; Mercante, F.M.; Tomazi, M.; Zanatta, J.A.; Concenço, G.; Silva, W.M.; Retore, M. Integrated crop–livestock system in tropical Brazil: Toward a sustainable production system. *Agric. Ecosyst. Environ.* **2014**, *190*, 70–79.
19. Antoneli, V.; Mosele, A.C.; Bednarz, J.A.; Pulido-Fernández, M.; Lozano-Parra, J.; Keesstra, S.D.; Rodrigo-Comino, J. Effects of Applying Liquid Swine Manure on Soil Quality and Yield Production in Tropical Soybean Crops (Paraná, Brazil). *Sustainability* **2019**, *11*, 3898.
20. Libralato, S.; Christensen, V.; Pauly, D. A method for identifying keystone species in food web models. *Ecol. Model.* **2006**, *195*, 153–171.

21. Christensen, V.; Walters, C.J. Ecopath with Ecosim: Methods, capabilities and limitations. *Ecol. Model.* **2004**, *172*, 109–139.
22. Dalsgaard, J.P.T.; Oficial, R.T. *Modeling and Analyzing the Agroecological Performance of Farms with Ecopath*; ICLARM: Manila, Philippines, 1998; ISBN 9718709851.
23. Hiltbrunner, E.; Aerts, R.; Bühlmann, T.; Huss-Danell, K.; Magnusson, B.; Myrold, D.D.; Reed, S.C.; Sigurdsson, B.D.; Körner, C. Ecological consequences of the expansion of N<sub>2</sub>-fixing plants in cold biomes. *Oecologia* **2014**, *176*, 11–24.
24. Dalsgaard, J.P.T.; Oficial, R.T. A quantitative approach for assessing the productive performance and ecological contributions of smallholder farms. *Agric. Syst.* **1997**, *55*, 503–533.
25. Spitz, J.; Ridoux, V.; Brind'Amour, A. Let's go beyond taxonomy in diet description: Testing a trait-based approach to prey–predator relationships. *J. Anim. Ecol.* **2014**, *83*, 1137–1148.
26. Byron, C.J.; Jin, D.; Dalton, T.M. An Integrated ecological–economic modeling framework for the sustainable management of oyster farming. *Aquaculture* **2015**, *447*, 15–22.
27. Saltelli, A.; Ratto, M.; Andres, T.; Campolongo, F.; Cariboni, J.; Gatelli, D.; Saisana, M.; Tarantola, S. *Global Sensitivity Analysis: The Primer*; John Wiley & Sons: Ipsra, Italy, 2008; ISBN 0470725176.
28. Chea, R.; Guo, C.; Grenouillet, G.; Lek, S. Toward an ecological understanding of a flood-pulse system lake in a tropical ecosystem: Food web structure and ecosystem health. *Ecol. Modell.* **2016**, *323*, 1–11.
29. Odum, E.P. The strategy of ecosystem development. In *The Ecological Design and Planning Reader*; Springer: New York, NY, USA, 2014; pp. 203–216.
30. Alongi, D. *The Energetics of Mangrove Forests*; Springer Science & Business Media: Dordrecht, The Netherlands, 2009; ISBN 140204271X.
31. Ulanowicz, R.E.; Goerner, S.J.; Lietaer, B.; Gomez, R. Quantifying sustainability: Resilience, efficiency and the return of information theory. *Ecol. Complex.* **2009**, *6*, 27–36.
32. Paramesh, V.; Parajuli, R.; Chakurkar, E.B.; Sreekanth, G.B.; Kumar, H.B.C.; Gokuldas, P.P.; Mahajan, G.R.; Manohara, K.K.; Viswanatha, R.K.; Ravisankar, N. Sustainability, energy budgeting, and life cycle assessment of crop- dairy-fish-poultry mixed farming system for coastal lowlands under humid tropic condition of India. *Energy* **2019**, *188*, 116101.
33. Kremen, C.; Iles, A.; Bacon, C. Diversified farming systems: An agroecological, systems-based alternative to modern industrial agriculture. *Ecol. Soc.* **2012**, *17*, 1–19.
34. Cruz-Escalona, V.H.; Morales-Zárate, M.V.; Franco-López, J.; Abitia-Cárdenas, L.A.; Hernández-López, A.; Marín-Enríquez, E.; González-Acosta, A.F. Food-Web Structure and Functioning of Coastal Marine Ecosystems: Alvarado Lagoon and Adjacent Continental Shelf, Northern Gulf of Mexico. *Open Fish Sci. J.* **2018**, *11*, 73–94.
35. Ulanowicz, R.E. *Growth and Development: Ecosystems Phenomenology*; Springer Science & Business Media: Dordrecht, The Netherlands, 2012; ISBN 1461249163.
36. Colléter, M.; Guitton, J.; Gascuel, D. An introduction to the EcoTroph R package: Analyzing aquatic ecosystem trophic networks. *RJ* **2013**, *5*, 98–107.
37. Torres, M.Á.; Coll, M.; Heymans, J.J.; Christensen, V.; Sobrino, I. Food-web structure of and fishing impacts on the Gulf of Cadiz ecosystem (South-western Spain). *Ecol. Model.* **2013**, *265*, 26–44.
38. Moraine, M.; Duru, M.; Therond, O. A social-ecological framework for analyzing and designing integrated crop–livestock systems from farm to territory levels. *Renew. Agric. Food Syst.* **2017**, *32*, 43–56.
39. Manjunath, B.L.; Paramesh, V.; Mahajan, G.R.; das, B.; Reddy, K.V.; Chakurkar, E.B.; Singh, N.P. Sustainability through resource recycling, soil fertility and carbon sequestration from integrated farming systems in west coast India. *Bioscan* **2017**, *12*, 1–6.

