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Sustainability Interventions on Agro-Ecosystems: An Experience from Yunnan Province, China

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Abstract: Increasing agricultural production, without having a pronounced negative impact on ecosystems, continues to be a massive challenge. Interventions in sustainability that improve agro-ecosystems are thus crucial. Current literature focuses on sustainability concepts, assessment tools, and intervention impacts, yet lacks in intervention mechanisms and implementation processes. Therefore, this study aims to present an intervention framework on agro-ecosystems that helps transform sustainability concepts into implementation actions. We first create the intervention framework on agro-ecosystems using a systematic approach, and then analyze the intervention mechanism. Next, we formulate the agro-ecological sustainability index (AESI) and its sub-indices to assess the results of interventions. We find that, by integrating interventions, we can reverse the sustainability trend from deterioration to recovery and improvement; however, with a spatial difference. We highlight that the process for a successful intervention comprises (1) utilizing an integrated intervention portfolio, (2) acting with a long-term perspective, (3) utilizing adaptive implementation, and (4) strengthening local institutions. We suggest closely monitoring the impact of interventions, diversifying farmers' income sources, and enhancing capacity building for young generations. Additionally, we suggest conducting multidisciplinary research and strengthening local government capacity to hedge against future risks. Our intervention framework and Yunnan's intervention experience provides a useful lesson for other policymakers and researchers to achieve the Sustainable Development Goals.

Keywords: policy intervention; intervention framework; agro-ecological sustainability index

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Citation: Fan, J.; Fan, X.; Jintrawet, A.; Weyerhaeuser, H. Sustainability Interventions on Agro-Ecosystems: An Experience from Yunnan Province, China. *Sustainability* **2021**, *13*, 5698. https://doi.org/10.3390/su13105698

Academic Editor: Antonino Galati

Received: 15 April 2021
Accepted: 18 May 2021
Published: 19 May 2021

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1. Introduction

With growing population pressure, industrialization, and urbanization, agriculture is facing the huge challenge of producing enough food to feed the world without environmental degradation [1–3]. The "Green Revolution", which includes crop genetic improvements, systematic use of mineral fertilizers, chemical pest and disease control, effective water use, and farm mechanization, has produced an impressive increase in crop yield since the second half of the 20th century. Expansion of agricultural land and intensification further contributed to increased global food production [4–6], which has tripled in the past fifty years. Furthermore, the area under irrigation has doubled, and the use of mineral nitrogen fertilizers has increased sevenfold [5]. As a result, modern agricultural systems are meeting global food demands. However, global food demand is quickly increasing and, consequently, the demand for crop production is projected to increase by 100–110% from 2005 to 2050 [1].

The high intensity of agricultural production has brought a considerable environmental burden and thus made agro-ecosystems partly inefficient and unsustainable. Excessive use of mineral nitrogen and phosphorus causes soil degradation, water pollution, and eutrophication [4,5]. Intensive use of chemical pesticides raises problems such as pest

resistance, human health problems, and loss of biodiversity [5]. Agricultural land expansion and large consumption of fresh water leads to deforestation, salinization, and water scarcity [7,8]. Intensive use of fossil fuel and fossil fuel-based inputs results in high levels of greenhouse gas emission and thus contributes to climate change [5,7]. All these aspects have brought about public awareness, the desire for agriculture to produce enough food without environmental degradation, and calls for interventions in sustainability on agro-ecosystems [5]. Moreover, interventions that develop synergies between different agro-ecological components have been defined as a priority within the Sustainable Development Goals (SDGs) of the United Nations [5,9,10].

The concept of agricultural sustainability involves environmental, social, and economic dimensions aims on not only improving the current agro-ecosystems but also satisfying future generations' needs [11,12]. Ever since the 1990s, the definition, principle, and implications of the term "sustainability" have been widely discussed [13–15]. At the same time, conceptual frameworks were developed to understand the complexity of agro-ecosystems, evaluate their sustainability, and provide sustainable agricultural transformation approaches for farmers and policy makers [7,16–20]. Different assessment tools in which indicators play an important role have also been developed or adapted to evaluate the performance of agro-ecosystems, namely: life cycle assessment, cost–benefit analysis, or environmental impact assessment [16,17,21–24]. While this concept and analytical frameworks of sustainability are well studied and many researchers urge agricultural sustainability transformation [5,25], implementations of interventions in sustainability on agro-ecosystems are still not widely adopted. This is due to the large gap between theoretical concepts and implementation actions, as unclear implementation processes, incapable institutions, and unadaptable interventions often prevent implementation [24,26]. Moreover, in the few reports on sustainability intervention (i.e., studies in African countries [27], Latin American countries [28], and China [29,30]), impact assessments are more common than providing information on intervention mechanisms and actionable implementation experiences. Therefore, it is necessary to study sustainability intervention mechanisms and implementation processes to help transform sustainability concepts into implementation actions.

This study aims to present an intervention framework on agro-ecosystems and actionable implementation experience that will help transform sustainability concepts into implementation actions. Yunnan province is a highly diverse area in agro-ecological terms and was therefore chosen as an example to demonstrate how selected sustainability interventions are implemented. We assess the effects of interventions and draw lessons from our analysis. In doing so, we first created an intervention framework of agro-ecosystems and used the framework to analyze the intervention mechanism and then formulate an agro-ecological sustainability index (AESI) and its sub-indices to evaluate the effects of the different interventions. We also analyzed the spatial difference of the interventions among three selected prefectures. We conclude with lessons from Yunnan's intervention experiences, links between intervention results and SDGs, and suggestions to counteract possible future risks. We strongly believe that our intervention framework and Yunnan's interventions in sustainability experience provides useful information for policymakers and researchers elsewhere to achieve the SDGs.

2. Materials and Methods

2.1. Study Area

Yunnan province is a mountainous area, located in southwestern China, bordering Myanmar, Laos, and Vietnam. Its complex topography paired with a climate dominated by two monsoons (the East Asian monsoon and South Asian monsoon) results in rich biodiversity, a wide range of landscapes, and different climatic conditions (e.g., tropical forest in the south and mountains with glaciers in the north) [31,32]. Maize is the major crop in the province as most of the farmland in this region has a more than three-degree slope [32]. However, other agricultural products are still planted, including rice, wheat, sugarcane, tobacco, and fruits [32,33]. Although several rivers, such as the Yangtze, Pearl,

and Mekong, flow through the province, it is still vulnerable to droughts due to uneven water distribution and a lack of water conservation facilities [34]. Moreover, soil erosion and rock desertification are major concerns with respect to agricultural development [34]. In order to protect the fragile ecosystem and improve agricultural production, intervention programs such as the Sloping Land Conversion Program and Comprehensive Treatment Program of Rocky Desertification in Karst Area were launched in the 2000s [34].

2.2. Sustainability Intervention Framework

We used a systematic approach to holistically identify the key actors and gain a better understanding of their interactions during the interventions on agro-ecosystems [35,36]. Since the integrated agro-ecosystems had already been well-studied, our research interest was the intervention mechanism. We therefore simplified the agro-ecosystems and focused on decision-making and implementation processes. We also did not consider social components in our framework, as the interventions in this study mainly addressed biophysical components. Thus, social impact was beyond the scope of this study. We reviewed literature from related fields, such as infrastructure development [37], environment protection [38,39], energy production [40], and water management [41], to understand the policy decision-making and implementation process in Chinese administrative system. Finally, based on different analytical schemes [29,39,40,42,43] and authors' own experience, we created a framework to describe and analyze the intervention mechanisms. Generally, an agricultural system is a modified natural system based on the modification of structure and functions through farming management and external inputs, e.g., introducing crops, reshaping landscapes, and changing nutrient dynamics. It is surrounded by and embedded in a natural ecological system. The natural ecological system provides fundamental functions such as soil formation and nutrient recycling, water purification, and pollination to support agricultural production. In return, the feedback from agricultural practices affects the ecological system. These impacts can be negative, such as deforestation, chemical pollution, and eutrophication, or positive, such as reducing nutrition stress, improving water cycle, and protection from wind [43,44]. Policy interventions can be applied to strengthen positive impacts or reduce negative impacts on ecosystems (Figure 1).

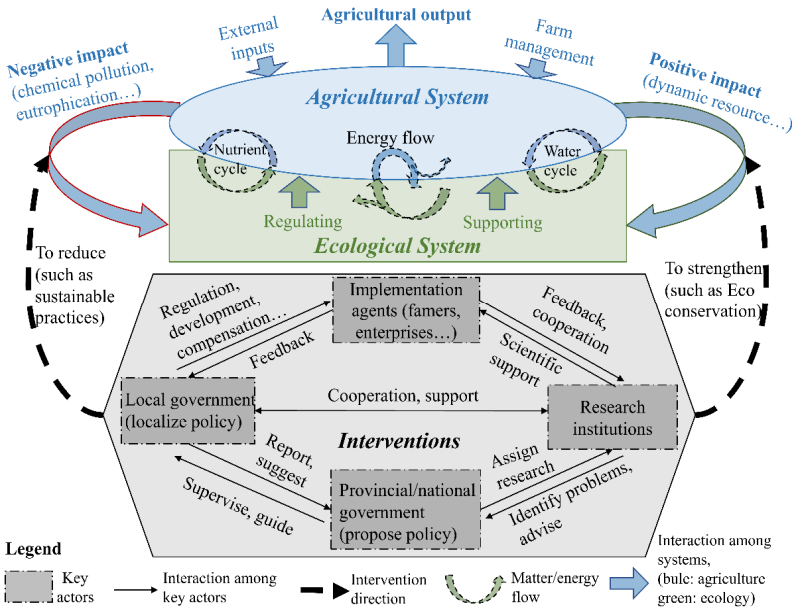

Figure 1. Intervention framework on agro-ecosystems. The blue ellipse box represents the agricultural system. The green box represents the ecological system, and the light grey box represents the intervention system. The ecological system provides services for the agricultural system while the agricultural system impacts the ecological system. Interventions can be applied to reduce or strengthen these impacts. Matter and energy flow span agricultural and ecological systems.

2.3. Agro-Ecological Sustainability Index (AESI)

We used the index-based method by Van Cauwenbergh et al. (2007) [16] to assess the effects of interventions on agro-ecosystems as it is reliable, simple, and widely used [16,17,21–24]. Based on the integrated agro-ecosystem intervention framework (Figure 1), we classified three indices, namely, agricultural output index (AOI), negative ecological impact index (NEI), and positive ecological impact index (PEI). We then used them to further formulate AESI. The selection of indicators must consider the representation of indices, the research interests, and the availability of data [16,26]. Therefore, we chose the 12 most representative and readily available variables from the Yunnan Statistic Yearbooks (http://stats.yn.gov.cn/tjsj/tjnj/, accessed on 20 September 2020) [33] to formulate the three sub-indices represented in Table 1. Each sub-index consists of several variables. For example, the "negative ecological impact index" involves the total cropping area and the usage of chemical fertilizer, pesticides, plastic mulch, and water. All variables have different dimensions and weights; therefore, we first standardized the variables to use the entropy method to calculate weights as follows [45]:

Table 1. Components of AESI formulated in our study.

Index	Sub-Indices	Variables
Agro-ecological sustainability index (AESI)	Agricultural output index	Grain production (rice, wheat, maize, tubers)
		Cash crop production (sugar cane, oilseeds, tobacco)
		Fruit production
		GDP from agriculture (provincial/prefecture scales)
	Negative ecological impact index	Chemical fertilizer usage
		Pesticide usage
		Plastic mulch usage
		Water usage
		Total cropping area
	Positive ecological impact index	Reforestation area (restore damaged woodland)
		Water reservoir capacity (infrastructures for hilly areas to collect and distribute water to cope with droughts)
		Irrigation area (for dryland, expanding irrigation areas mean bringing more water to local systems and allocating water effectively, thus considered a positive impact)

$$x'_{ij} = \frac{x_{ij} - x_{j,min}}{x_{j,max} - x_{j,min}} \quad (1)$$

where, x_{ij} is the value of variable j in year i and x'_{ij} is its standardized value. $x_{j,min}$ and $x_{j,max}$ represent the minimum and maximum values, respectively. We then calculated the weight (w) for each variable according to its variation and entropy (from Equations (2) to (5)). The proportion (y) for variable j in year i:

$$y_{ij} = x'_{ij} / \sum_{i=1}^{m} x'_{ij} \quad (2)$$

The entropy (e) for variable j:

$$e_j = -\frac{1}{ln\ m} \sum_{i=1}^{m} y_{ij} \times ln\ y_{ij} \quad 0 \le e_j \le 1 \quad (3)$$

The entropy redundancy (d) for variable j:

$$d_j = 1 - e_j \quad (4)$$

The weight (w) for variable j:

$$w_j = d_j / \sum_{j=1}^{n} d_j \quad (5)$$

where m and n are the number of years and the number of variables, respectively. The index value (I) in year i can thus be calculated:

$$I_i = \sum_{j=1}^{n} w_j \times x'_{ij} \quad (6)$$

The AOI, NEI, and PEI for Yunnan province and 16 prefectures were all calculated using Equation (6), with values for the respective index (I) ranging from zero to one. Next, we combined the three indices to formulate the AESI [46]. Since a higher value of negative ecological impact index meant lower sustainability of the system, we therefore used one minus negative ecological impact index during the AESI calculation.

$$AESI_i = \Phi\left(\frac{1}{\mid K \mid} \sum_{k \in K} I_{i,k}\right) \quad (7)$$

where $AESI_i$ is the agro-ecological sustainability index value in year i. $\mid K \mid$ is the number of indices; as mentioned above, in this study, $\mid K \mid = 3$. Φ is the inverse gaussian distribution and its cumulative distribution function is used to generate values. This calculation was performed by the Python programming library SciPy (scipy.stats.invgauss) [47].

To project the future values of indices, we used the creeping trends method [48,49], and the key idea was that the current data set was more important than historical data sets. This method uses ordinary least square to estimate partial trends and uses harmonic weights to determine the importance of each trend. The detailed calculation was previously described by Lloyd (2015) [49].

2.4. Data

Both provincial and prefectural data from the year 2008 to 2019 for the twelve variables listed in Table 1, were obtained from the Yunnan Statistic Yearbooks (http://stats.yn.gov.cn/tjsj/tjnj/, accessed on 20 September 2020) [33] to calculate sub-indices of AESI. For intervention policies, we primarily reviewed sustainability interventions from the official websites of government departments (https://nync.yn.gov.cn/zwgk/, accessed on 20 September 2020, http://www.yn.gov.cn/zwgk/, accessed on 21 September 2020 and http://lcj.yn.gov.cn/html/zhengwugongkai/, accessed on 11 November 2020) [50–52]. We then selected the policies that covered much of the province and were related to agriculture and ecology dimensions. Literature databases (Web of Science, Scopus, and Google Scholar) were searched with the keywords "Sustainability", "Intervention", and "Yunnan", to search for related policies. In total, six provincial policies, including programs, plans, regulations, and compensation policies, were selected (Table 2) as the main interventions to study their effect on agro-ecosystems.

Table 2. Details of the selected intervention policies in Yunnan province.

Name	Objectives	Time Frame	Key Points	References
Comprehensive treatment program of rocky desertification in karst area	Curb desertification expansion, stabilize ecosystem, optimize agricultural structure	2008–2020	1. Central government funds the key counties, local governments fund the other counties. Standard: 2000–2500 CNY per hectare (286–357 USD). 2. Conserve fragile vegetation and reforest. 3. Improve grassland and develop husbandry properly. 4. Build terraced farmland and water facilities.	[29,53]

Table 2. *Cont.*

Name	Objectives	Time Frame	Key Points	References
Well-facilitated farmland construction program	Stabilize agricultural production, construct at least 800,000 hectares well-facilitated farmland	2014–2020	1. Multiple funding sources (government, agricultural companies, farmers). 2. Merge fragmented farmland. 3. Improve soil quality. 4. Build irrigation facilities. 5. Redesign road and construct farmland shelterbelt. 6. Digitalize farmland information on a monitoring map.	[54,55]
Modern highland agriculture plan	Enlarge agricultural production, secure food safety, improve sustainability, enhance innovation and technology	2016–2020	1. Optimize the spatial distribution and structure of agriculture. 2. Enhance agricultural infrastructure (land, irrigation, machine, technology, markets, information) 3. Encourage moderate-scale land merger; promote agricultural brand; integrate agriculture, manufacturing, and service sectors. 4. Protect arable land quantitatively and qualitatively; develop water-efficiency and circular agriculture; protect environment (zero increase in chemical fertilizer and pesticide).	[56]
Tighten pesticide regulation	Eliminate toxic pesticide and develop biopesticide, improve pesticide efficiency and quality	2017–2025	1. Support registration of environmental friendly pesticide; restrict highly risky pesticides and withdraw registration of toxic pesticide. 2. Move pesticide producers to the chemistry industry zone, eliminate high pollution production capacity. 3. Tighten sales license (qualified distributors, traceable sales). 4. Help farmers to choose and use pesticide scientifically (increase efficiency, decrease quantity). 5. Strengthen law enforcement capacity, punish illegal activities.	[57]
Ecological compensation	Build compensation mechanism that covers major ecological fragile areas by 2020, promote green production manner and green lifestyle	2017–2020	1. Set up funds at provincial, prefecture, and county level governments. 2. Cover major ecological systems such as forest, grassland, watershed, and farmland. 3. Compensation from higher-level governments to lower-level governments if ecological standards are achieved, deduction otherwise. 4. Beneficiaries compensate protectors; downstream areas compensate upstream areas. 5. Trans-regional cooperation.	[58,59]
Soil pollution prevention	Stop deteriorated soil pollution by 2020, improve soil quality by 2030	2017–2030	1. Clarify soil quality situation; build soil monitoring network. 2. Protect existing farmland from pollution. 3. Prevent pollution of newly developed farmland. 4. Control pollution source, especially mining sites and agricultural pollution.	[60]

3. Results

3.1. The Intervention Mechanism and Implementation Process

As Figure 1 shows, the intervention mechanisms involved the provincial government, local governments (including prefecture, county, and township), research institutions, and final implementation agents, such as farmers and enterprises. The provincial government proposed and drafted policies (such as regulations and development plans) which were

usually based on experiences from pilot projects, problems from bottom-up feedback, and suggestions from research institutions. Drafts were then sent to different departments, local governments, and other public stakeholders to collect broad feedback and suggestions. Beyond its own intervention policies, the provincial government also needed to detail national intervention programs (e.g., the "Comprehensive Treatment Program of Rocky Desertification in Karst Area" and the "Well-facilitated Farmland Construction Program") to address objectives, priorities, key strategies, responsibilities, and major projects. Table 2 lists the details of six intervention policies.

The implementation process of the intervention policies started after several rounds of consultation and revision by local governments. Supervised by the provincial government, local governments needed to adapt the interventions based on their respective conditions and applied them to the implementing agents/clients (such as farmers and pesticide retailers) through different approaches including, but not limited to, compensation, regulatory frameworks, training, and extension. Moreover, several agricultural technicians were deployed at the township level to help farmers. Research institutions and universities joined local governments to provide scientific and technical support, including new germplasm development and utilization, sustainable practices identification, and training for farmers and extension workers. Research institutions also identified agricultural and ecological problems and suggested solutions, provided access to early warning systems, and advised the government. In some cases, research institutions even led project implementation, as described in a previous study [61]. Farmers in ecologically sensitive areas usually participated in conservation projects and received compensation from county-level governments directly; farmers in major agricultural areas tested sustainable practices such as crop residue mulching, soil-based fertilizer application, right-time irrigation, and biological pest control to contain environmental pollution and resource degradation [62].

3.2. Intervention Results at the Provincial Level

In order to better understand the causal links between agro-ecosystems and interventions, we divided the past twelve years into three phases which were classified as "high inputs high outputs", "over-exploitation", and "recovery with more interventions" based on the system performance (Figure 2A). From 2008 to 2012, agricultural output increased tremendously with the same pattern of negative ecological impact, which suggested that high agricultural output growth was mainly achieved by the intensive use of inputs. Therefore, this period was described as the "high inputs high outputs" phase. From 2013 to 2016, the agro-ecological system was over-exploited with a decreasing AESI. In this "over-exploitation" phase, the agricultural output stagnated, the use of inputs such as chemical fertilizers and pesticides, however, continued to increase, resulting in a high negative ecological impact. In the third "recovery with more interventions" phase, as more interventions (such as pesticide regulation and soil pollution prevention) were introduced, agricultural outputs started to increase again from 2017 and the negative ecological impact index started to decrease in 2018, resulting in a sustainability recovery as depicted by AESI.

In the "high input high output" phase (2008–2012), the main local interventions were driven by a national conservation program (the Comprehensive Treatment Program of Rocky Desertification in Karst Area) as local agricultural problems had not yet emerged. Since the application of the conservation program in 2008, the positive ecological impact index increased immediately because of the expanding reforestation area (Figure 2A).

In the "over-exploitation" period, the agro-ecological system could not be sustained as the agricultural output index stagnated while the negative ecological impact index still increased. Therefore, the interventions were focused on stabilizing and increasing agricultural production at this period. The Well-facilitated Farmland Construction program started in 2014 and was a typical intervention that aimed to improve agricultural production through merging fragmented farmland and updating infrastructures. After its implementation, the positive ecological impact index started to increase (Figure 2A). However, the agricultural output index did not increase immediately because of a delayed

effect. Moreover, a comprehensive agricultural development plan (the Modern Highland Agriculture Plan) was initiated in 2016, attempting to eliminate unsustainable upland agricultural practices. Numerous measures were brought in to improve agricultural efficiency, curb environmental pollution, as well as to stabilize or sustainably increase agricultural production, through innovations and appropriate technologies. Zero increase in mineral fertilizer and pesticides use were also promoted and emphasized in the plan. The result of this intervention was observed in the next few years, with a regrowing agricultural output index and a decreasing negative ecological index (Figure 2A).

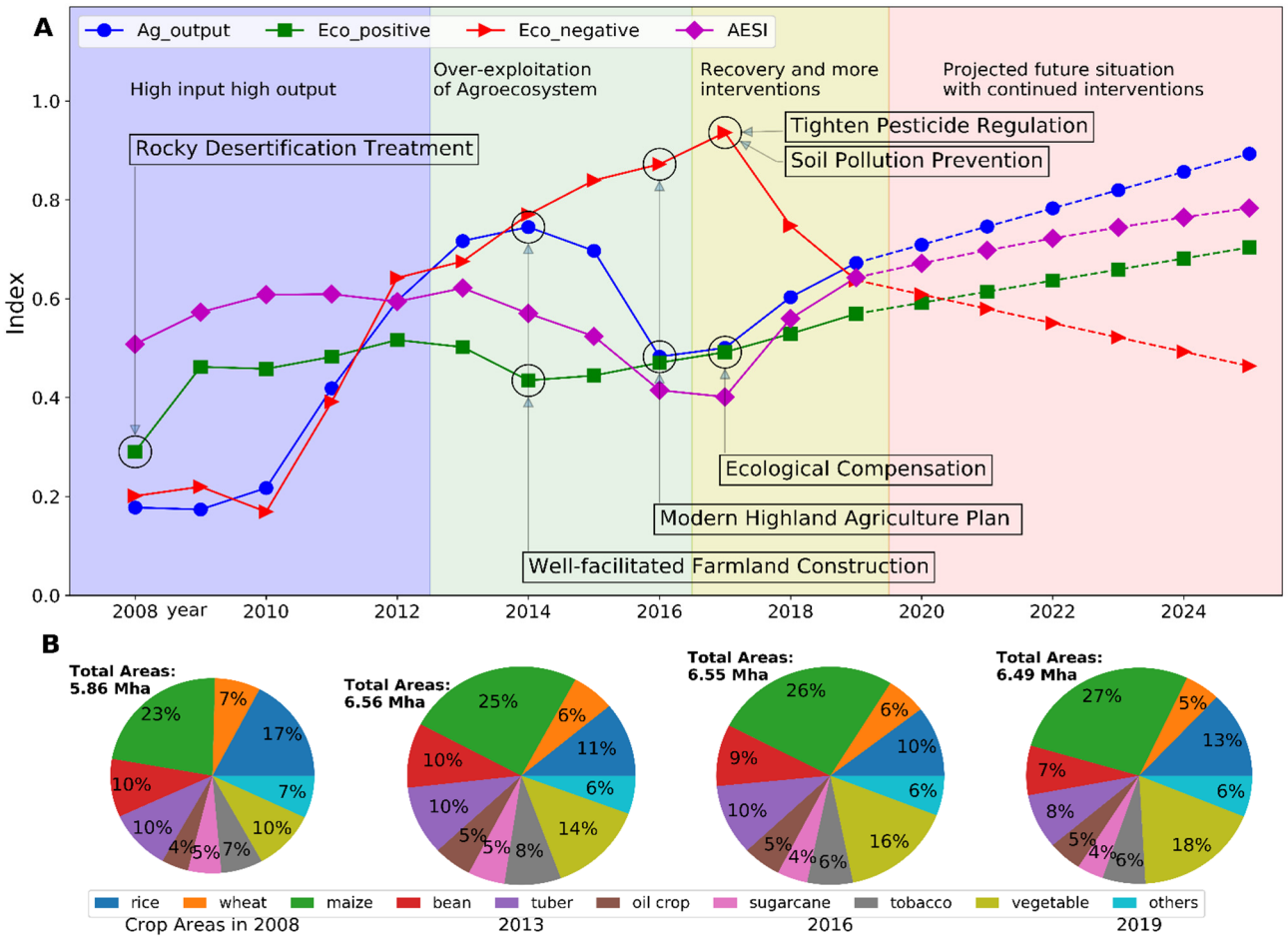

Figure 2. The evolution of agro-ecosystems in Yunnan province, China. (**A**) Intervention timeline, Ag_output = agricultural output index, Eco_positive = positive ecological impact index, Eco_negative = negative ecological impact index, and AESI = agro-ecological sustainability index, circle and arrow indicate interventions' main object and start year. (**B**) Changes in crop sown areas, pie size refers total sown area size.

In the "recovery with more intervention" period (2017–2019), three more interventions (the Tighten Pesticide Regulation, Ecological Compensation, and Soil Pollution Prevention) were implemented to promote green production and lifestyle. With the effects of these interventions, agricultural output started to increase again after 2017. The negative ecological impact index decreased after 2018, the positive ecological impact index had continuously increased, and, finally, the sustainability of agro-ecosystem was reversed.

Following the current trends, with continued interventions, the projected agricultural output index would be generally growing, the negative ecological impact index would be decreasing, and the positive ecological impact index would be increasing. The upland agro-ecological systems would thus be more sustainable in the future. Additionally, the growing agricultural output and sustainable agro-ecosystem will directly support food

security, poverty reduction, environment protection, climate change, and other issues and policies. Therefore, this would contribute to the SDGs of the United Nations' 2030 agenda.

In the past twelve years, the cropping area has not changed considerably, except for maize and vegetables which increased by 4% and 8%, respectively (Figure 2B). However, the total cropping area increased from 5.86 million hectares in 2008 to 6.56 million hectares in 2013 and was then kept stable. The stable crop planting areas since 2013 suggest that planting areas were not the main reason behind the improvement of system sustainability. Instead, the interventions were mainly focused on improving agro-ecological efficiency and curbing environmental problems, thus improving the system.

3.3. Localized Interventions among Prefectures

Different areas had different conditions and problems. Therefore, the agro-ecological sustainability differed temporally and spatially between prefectures over the past twelve years (Figure 3A–E). Local governments were responsible for implementing intervention policies. The interventions were adapted from provincial policies because the major reasons behind agro-ecological sustainability deterioration were different. Three prefectures, namely Baoshan, Yuxi, and Wenshan from the west, middle, and east parts of Yunnan province, respectively, were selected to demonstrate different problems and interventions (Figure 3A).

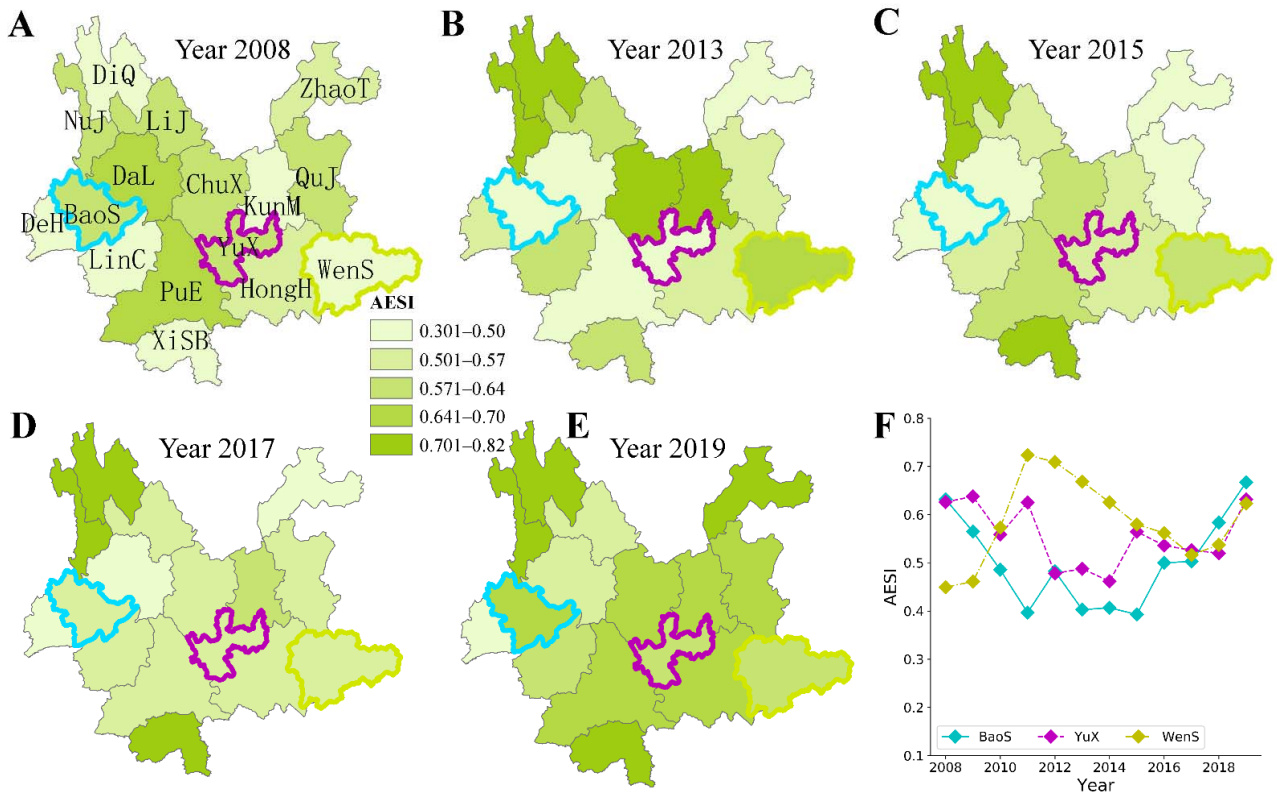

Figure 3. Prefecture-level agro-ecological sustainability index (AESI) in Yunnan province. The names on map are the abbreviations of prefectures, for example: WenS = Wenshan prefecture.

Located in the uplands of the western part of Yunnan province, the natural conditions in Baoshan prefecture were not suitable for the economic production of staple crops. Thus, agricultural production was boosted by a massive increase in inputs, which caused a decrease in the agro-ecological sustainability from 2008 to 2011. To reverse the negative trend, the critical task was to improve the production efficiency. Before the provincial's Well-facilitated Farmland Construction Program, similar interventions had already been implemented to improve farmland infrastructure—especially irrigation—to protect natural

resources and curb environmental pollution from agricultural activities [63,64]. These interventions stopped the decline in sustainability (Figure 3F). Following further interventions of the provincial administration (the Modern Highland Agriculture Plan and Tighten Pesticide Regulation), local governments started the "Green Agriculture Transition" in 2016 which aimed at achieving no increase in mineral fertilizer and chemical pesticide use. In practice, this was achieved by fertilization based on soil tests, replacing mineral fertilizer with organic fertilizer, and using more bio-pesticides [65]. The sustainability of the local agro-ecosystems in Baoshan prefecture was finally improved after these interventions (Figure 3F).

The sustainability of Yuxi prefecture was decreasing in the period between 2008 and 2014 mainly due to soil degradation. Since then, the Comprehensive Treatment Program of Rocky Desertification in Karst Area was expanded [66] and a 9.7 billion CNY (1.4 billion USD) localized ecological agriculture development plan, which included 32 sub projects, was implemented in 2016, covering agricultural structure change (optimizing the spatial distribution of crops and properly replacing high-input crops with low-input crops), agriculture innovation demonstration, agricultural processing, agriculture and service integration, ecological restoration, and technology support [67]. Finally, the sustainability of the local agro-ecosystem was improved (Figure 3F).

Wenshan prefecture is situated in a karst area in the eastern part of Yunnan province and was severely affected by rocky desertification. Therefore, the national Comprehensive Treatment Program of Rocky Desertification in Karst Area covered Wenshan prefecture in its first phase in 2008 [68]. Thus, the agro-ecological sustainability index for Wenshan prefecture quickly increased from 2008 to 2012 (Figure 3F). Later, the agro-ecological sustainability index gradually deceased. However, this trend was reversed (Figure 3F) with more localized interventions, such as training for sustainable use of chemical fertilizer and pesticide reductions [69].

4. Discussion

In this article, we studied the sustainability interventions on agro-ecosystems in Yunnan province, aiming to find useful and practical implementation experience that can help achieve agro-ecosystem transformation and eventually SDGs. Therefore, we first studied the intervention mechanisms and implementation processes, followed by the evolution of agro-ecosystems caused by the respective interventions, and, finally, the spatial differences of interventions. We further discuss the major lessons and limitations from these interventions, and the impact that sustainability interventions addressed SDGs.

4.1. Lessons from Yunnan's Experience

The first lesson learned is that interventions should be combined with an integrated planning process for the targeted areas because of the complexity of the agro-ecosystems. Single or non-linked interventions are therefore inadequate and could have an adverse effect on the system [70]. Agricultural, environmental, and social-economic issues and conditions are simultaneously and systematically assessed and diagnosed during the proposal drafting and implementation processes. All stakeholders' interests are inclusively integrated, including different levels of government, research institutions, farmers, and enterprises. All stakeholders must be involved in the proposal development and implementation processes, though the governments are usually dominant in the processes of the framework (Figure 1). All available policy instruments are integrated: regulations, development plans, ecological compensations, and national programs are combined to finally improve the sustainability of agro-ecosystems.

The second lesson learned is that interventions should have a medium- or long-term view, i.e., 3–5 or 5–10 years, respectively. The impacts of some interventions (such as ecological conservation and soil improvement) may not be observed immediately, and a time lag may persist for years or even decades [70,71]. Therefore, all interventions should be set to achieve long-term objectives, and long-term financial commitments from the

government are required. Long-term planning and implementation support further require a steadfast government commitment, which is a huge challenge for many countries as they are restricted by electoral cycles [29]. Many of Yunnan's interventions have lasted for about 10 years (Table 2) and are likely to be continued to overcome problems, giving the Chinese government an advantage to carry out long term changes in rural areas.

The third lesson learned is that interventions must be adaptive and flexible in nature. Given the heterogeneity of prefectures and their agro-ecosystems, local interventions must be adapted to fit their corresponding situations. Different intervention priorities are given to different prefectures; for example, Wenshan prefecture focuses on rocky desertification treatment while Baoshan prefecture focuses on agricultural facilities improvement. Moreover, adaptive governance is essential for dealing with complex systems [72]. With changes in environment, knowledge, and technology, interventions are evolving; for instance, new sustainable practice may be introduced, compensation standards may increase, and evaluation processes may be changed.

The fourth lesson learned is that there must be a functional institution to lead the implementation. Ad hoc committees and voluntary institutions, rent-seeking approaches, and weak leadership may result in a failed intervention, even though the underlying policy was good [73]. Therefore, a functional institutional framework with harmonic implementation mechanisms and data sets is essential [74] and strengthening the local governments' execution capacity is critical. The local governments play an important role in explaining policies, persuading farmers to adopt new practices, coordinating with other stakeholders, periodically reporting results to higher levels of government, and carrying out regulations.

4.2. Limitation and Future Improvement

Though the interventions in Yunnan province significantly improved the agro-ecological sustainability, some nuanced adverse outcomes have been reported. Xiao et al. (2020) [34] reported that inappropriate afforestation (e.g., inappropriate species) may increase evapotranspiration effects and an increase in drought risk. Chen and Cao (2013) [73] revealed that competition for the allocation of funds between different government departments undermines intervention effectiveness. Moreover, not all the concerns are addressed, especially for the poor, as some of them are reluctant to speak out due to asymmetric information and lack of ability during the policy consultation periods. The lack of information and progress about local intervention results available to the public is another weakness as it may discourage people from participating. The intervention framework in this study is generated from Yunnan's agro-ecosystems and excludes social components. Thus, such interventions generated in this study may not be successful if attempted in other areas. Other users who intend to use a similar approach to intervene in agro-ecosystems may need to modify the framework and choose indicators accordingly.

As the current limitations remain and future risks are inevitable, some modified strategies are needed to improve the interventions. First, monitoring and evaluation of the impact of interventions during implementation and after termination is necessary as adverse effects may be visible only after a certain time. Second, diversification of farmer's income and enhancement of farmers' positive attitudes towards sustainable practices are important to prevent them from reverting to their conventional practices [75]; without off-farm income, elder farmers may maintain their traditional practices. Third, investments in the young generation in rural areas are critical to pursue sustainable agriculture because the future of agricultural system needs knowledge-intensive technologies. Fourth, multidisciplinary research which includes agriculture, ecology, sociology, and economy is essential to provide scientific supports for sustainability intervention. Fifth, a strong but transparent local government is required to implement interventions and to deal with possible future risks. Finally, private sector involvement and educational transformation should also be encouraged as these create an information sharing network, change individuals' motivation and attitudes toward sustainability, and connect supply and demand closely [75,76].

4.3. Contribution to the SDGs

Agro-ecological interventions significantly contribute to the SDGs [29,77]. We believe that Yunnan's interventions presented in this paper also contribute to eight of the seventeen SDGs, especially SDG 2 (zero hunger) and SDG 15 (life on land). Each intervention may simultaneously contribute to multiple SDGs. For example, the Comprehensive Treatment Program of Rocky Desertification in Karst Area contributes to SDG 1 (no poverty) through increasing farmers' income in poor rural areas, SDG 2 through maintaining agro-ecosystems and improving land quality, SDG 6 (clean water) through increasing agricultural water use efficiency, SDG 10 (reduced inequality) through improving the economy of underdeveloped areas, SDG 13 (climate change) through strengthening the system's resilient capacity over climate related disasters, and SDG 15 through curbing desertification and restoring degraded forest. Moreover, synergies are common among joint interventions. For instance, the interaction of productivity improvement and climate mitigation may create synergies for SDG 2 [77]. However, there may be some trade-offs; for example, ecological conservation may favor SDG 15 but have a slightly negative impact on SDG 2.

Actions for improving the sustainability of agro-ecosystems are urgent as only nine years are left for the world to achieve the SDGs of the United Nations' 2030 agenda. Applying ecological concepts to better understand agro-ecosystems, innovate new agricultural practices, and empower people in system redesign is necessary [78]. A holistic view of producers, consumers, researchers, policymakers, and ecosystems during the sustainability intervention is also important. Long-term, context-based, integrated, and decisive policy interventions are needed for the world.

5. Conclusions

This study created an intervention framework of agro-ecosystems to analyze the sustainability intervention mechanisms and implementation processes, and then formulated the AESI and its sub-indices to evaluate the effects of interventions. As demonstrated by Yunnan province, the integrated policy interventions have reversed the sustainability trend from deterioration to recovery and improvement with a spatial difference. The keys to a successful intervention are an integrated policy portfolio, long-term view, adaptive implementation, and functional local institutions. We suggest closely monitoring the impact of interventions, diversifying farmers' income, enhancing capacity building for young generations, and changing people's motivation and attitudes toward sustainability. In addition, we also strongly support the policy for conducting multidisciplinary research and strengthening local government capacity to hedge against future risks. Given an urgent need for the world to achieve the demands for food as well as SDGs, this study provides a useful intervention framework and actionable implementation experience for other policymakers and researchers.

Author Contributions: Conceptualization, J.F. and A.J.; methodology, J.F.; writing—original draft preparation, J.F.; writing—review and editing, J.F., A.J., H.W. and X.F.; visualization, J.F.; supervision, X.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Yunnan Provincial Science and Technology Department under the program "High-end Foreign Experts".

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: We would like to thank editors and anonymous reviewers for their valuable suggestions and comments.

Conflicts of Interest: The authors declare no conflict of interest.

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