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Review

Compatibility between Conservation Agriculture and the System of Rice Intensification

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Abstract: Conservation Agriculture (CA) and the System of Rice Intensification (SRI) are both agroecologically-oriented production systems that support more productive, sustainable, and resource-conserving farming, with synergies arising from their respective assemblages of reinforcing agronomic methods. This review article examines the compatibility between CA and SRI, considering examples of their being utilized in complementary ways. The application of CA principles enhances the growth, yield, and performance of the crops grown under the cropping system as well as the health and resilience of the whole ecosystem. SRI practices create more favorable conditions for the development of crop plants below- and above-ground, including conditions that can be enhanced by CA management. SRI practices such as reduced plant density m^{-2} can elicit a better phenotypic expression of the genetic potentials of crops grown with CA. For these two agronomic systems to converge at the field level, some of their respective practices for plant, soil, water, and nutrient management need to be modified or aligned. One such adaptation is to practice SRI in CA systems on permanent, no-till, mulch-covered raised beds, with rainfall or irrigation water in the furrows between the beds furnishing and controlling water and providing weed suppression and improved nutrient recycling. SRI rice cropping can benefit from the CA practices of no-tillage, mulch soil cover, and diversified cropping, both in paddies and on raised beds. Several examples have shown that this convergence of cropping systems is feasible for smallholding farmers as well as for larger-scale producers and also that SRI practices within a CA system are amenable to considerable mechanization. Further research and experimentation are needed to identify and assess appropriate practices for capitalizing upon their synergies.

Keywords: agroecology; GHG emissions; cropping systems; mulch cover; synergies

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1. Introduction

Contemporary agricultural practices in their effort to increase crop yield and improve production efficiency have imposed heavy costs on the natural environment, both locally and globally. They contribute to the degradation of soil, water, and air quality, to declines in arable land, biodiversity, and ecosystem functioning and stability; to accelerated greenhouse gas (GHG) emissions that cause global warming; and to the deterioration of farmers' livelihoods in many rural communities [1–3]. As the vulnerability of agricultural production systems to the effects of climate change is increasing [2,3], the world needs farming practices that are more resilient and productive and that are able to store carbon in the soil rather than emit it, while also providing essential ecosystem services to farmers and to society.

The rice sub-sector exhibits the interconnections among the afflictions of food insecurity, poverty, and climate change with far-reaching global implications. As a staple food for about half of the world's population, rice plays a central role in feeding humanity [4]. Moreover, the growing of rice, particularly irrigated and rainfed lowland rice, supports the livelihoods of more than 1 billion people worldwide, most of them small-scale farmers, with 94% of global rice production coming from low- or middle-income countries [5].

Unfortunately, wetland rice is the food crop with the largest adverse ecological footprint, being responsible for roughly 10–12% of the agricultural sector's GHG emissions, and in some countries, up to 20% of their total GHG emissions [3]. Also, irrigated rice production is responsible for 24–30% of total freshwater withdrawals amid growing water scarcity [6]. Ploughing and puddling of irrigated rice paddies disaggregates soil structure and develops subsurface hardpans that impede the infiltration of water into lower soil layers and underground aquifers. This impairs soil-mediated ecosystem functions and services, changes landscape drainage patterns, affects water seepage, storage, and cycling, and contributes to the long-term depletion of groundwater resources, especially where pump irrigation is widespread [7,8].

Farmers' efforts to increase the yields of their puddled wetland rice rely heavily on exogenous inputs [9], with adverse effects on soil ecosystems and natural environments. Such strategies are encountering the limitations of diminishing returns, where the output produced from each additional unit of input is declining over time, prompting producers to use, counterproductively, ever-increasing amounts of purchased inputs [10].

Already it is evident that the rate at which rice production is growing is not sufficient to ensure global food security in 2050 [11]. And, with the current technology and trends in climate, the present rate is not likely to be sustained. Thus, there is a need to formulate and pursue strategies for rice production that both raise grain production and reduce detrimental environmental impacts.

Conservation Agriculture (CA) and the System of Rice Intensification (SRI) have shown global relevance for improved crop production, poverty alleviation, food security, and climate change adaptability and mitigation. However, so far, little has been done to take advantage of the possible combination of CA and SRI approaches so that rice farmers can intensify their cropping systems more sustainably. While as seen below, the integration of these two strategies for either organic or non-organic farming has attracted the attention of some researchers and practitioners, there is a scope and need for further consideration and experimentation to systematize and gain a deeper understanding of existing or possible synergies between the two systems [12–15].

1.1. Conservation Agriculture (CA)

CA is a system of land and farm management that aims to optimize farming productivity and ecosystem services at the field and landscape levels and to prevent soil degradation. It preserves and enhances soil health and biodiversity by stimulating regenerative biological processes both above- and below-ground. It is, in several ways, an alternative to the Green Revolution paradigm that has become predominant for agriculture. By 2019, CA was practiced globally on 205 million hectares across more than 100 countries, equally distributed in the global North and South. Since 2008, CA has been expanding at an annual rate of about 10 million hectares [16].

The three basic, interlinked principles and corresponding generic practices of CA are:

1. Continuous minimum or no mechanical soil disturbance: implemented by the practice of no-till seeding or the broadcasting of crop seeds and the direct placing of planting material into untilled soil; no-till weeding; and minimum soil disturbance from any cultural operation, harvest operation, or farm traffic. Sowing seed or planting crops directly into untilled soil and no-till weeding reduces runoff and soil erosion; minimizes the loss of soil organic matter via oxidation; reduces disruptive mechanical cutting and the smearing of pressure faces; promotes soil microbiological processes; protects and builds the soil structure and connected pores; avoids impairing the movement of gases and water through the soil; and promotes overall soil health.

2. Maintaining a permanent biomass mulch cover on the soil surface: implemented by retaining crop biomass, rootstocks, and stubbles and biomass from cover crops and other sources of biomass from ex situ sources. The use of crop residues (including stubbles) and cover crops reduces runoff and soil erosion; protects the soil surface; conserves water and nutrients; supplies organic matter and carbon to the soil system; promotes soil microbiological activity to enhance and maintain soil health, including the structure and aggregate stability (resulting from glomalin production by mycorrhiza); and contributes both to integrated weed, insect pest, and pathogen management and to integrated nutrient and water management.
3. Diversification of species in the cropping system: implemented by adopting a cropping system with crops in rotations and/or sequences and/or associations involving annuals and perennial crops, including a balanced mix of legume and non-legume crops and cover crops. The use of diversified cropping systems contributes to diversity in the rooting morphology and root compositions; enhances microbiological activity; enhances crop nutrition and crop protection via the suppression of pathogens, diseases, insect pests, and weeds; and builds up soil organic matter. Crops can include annuals, short-term perennials, trees, shrubs, nitrogen-fixing legumes, and pastures, as appropriate.

Each of these three pillars of CA can be practiced independently, but only when all three are implemented together can the CA system produce all the productivity and environmental benefits and be called CA. This is because the physical and biological processes promoted by the application of each practice function synergistically and result in greater crop productivity and farm output with more desirable environmental outcomes. To generate and sustain optimum factor productivity and ecosystem services, the basic CA practices should be combined with other, complementary practices for the integrated management of crops, soil, nutrients, water, pests, labor, energy, and land [16].

CA is now found with land-based production systems, both rainfed and irrigated, on all continents. Organic agriculture and regenerative agriculture systems qualify as CA when they incorporate the three principles of CA listed above [14]. While the agronomic principles of CA are broadly applicable, their practices for implementation are to be locally formulated, adapted to fit into any and all land-based agricultural systems, and combined with context-specific complementary practices [16].

1.2. System of Rice Intensification (SRI)

SRI is a crop management strategy that enhances the growth and performance of rice plants, paying attention to the soil biota, which has been ignored by conventional rice farming. Its practices improve the growing conditions for individual rice plants to enable each plant to achieve more of its genetic potential, becoming a more productive phenotype with more profuse growth of tillers, leaves, panicles, grains, and especially root systems [17].

Like CA, SRI practices are always to be adapted to local conditions and cropping systems, but the principles that guide SRI implementation are broadly applicable. With appropriate adaptations, they are beneficial also for other monocotyledonous crops such as wheat, maize, sugarcane, and millet [18,19]. The elements of SRI can be summarized as follows. (These are stated for crop establishment via transplantation, but they can be adapted for direct seeding of rice).

1. Early and careful establishment of single plants to preserve and mobilize their inherent growth potential for tillering and root development. Seedlings are transplanted before they start their fourth phyllochron of growth, i.e., beyond about 15 days after sowing, so as not to lose some of their potential for growth [20,21].
2. Minimize competition among plants by reducing plant density m^{-2} using wider spacing between plants and hills, allowing for the development of larger canopies and root systems. Spacing is to be optimized, however, not maximized. Best spacing

for single-plant hills, established in a square grid pattern, is usually about 25 × 25 cm, with 16 plants per m^{-2}.
3. Maintain mostly aerobic soil conditions by balancing the availability of water and oxygen in the soil to avoid the suffocation and degeneration of rice plant roots as well as of soil organisms such as bacteria and earthworms. In irrigated rice production, this involves alternate wetting and drying (AWD) or intermittent irrigation. Weeds are generally controlled with mechanical weeders in perpendicular directions, which causes surface soil aeration. Where there is no irrigation, SRI practices can be adapted for rainfed conditions.
4. Build up the soil's fertility by (a) enhancing soil organic matter to nourish the plants and soil biota and (b) maintaining the soil in mostly aerobic condition.

The practices that carry out these SRI principles are synergistically related, affecting and amplifying each other, as do the principles of CA. While each practice has some advantages for crop growth, the practices are most effective when implemented together [17]. Like CA, SRI can be practiced with or without synthetic fertilizer and agrochemicals, although with both seeking to enhance the soil biota and biodiversity, they discourage the application of types and amounts of chemical inputs that adversely affect life in the soil.

2. Compatibility between CA and SRI

The reason for introducing complementary SRI practices into rice-based CA systems, or conversely for moving SRI practices toward CA soil and water management, is to further increase their respective contributions to rice production and the natural environment, compared with the usual present practice of ploughing and puddling rice fields. Evaluating such effects is admittedly challenging because multiple, changing relationships are involved. Researchers accustomed to exploring the consequences of introducing a single agricultural practice would need to assess the implementation of combinations of these [22]. However, investigating the synergies between and among concurrent innovations should present many opportunities for useful research.

At first glance, SRI appears to be incompatible with CA because some of its practices, such as performing weeding operations with a surface soil-disturbing mechanical weeder, are contrary to those of CA. Also, SRI accepts farmers' usual methods for land preparation by ploughing and puddling their fields; it has not tried to modify this familiar part of paddy rice cultivation while it is, at the same time, changing many other accustomed practices. Current land preparation practices de-structure the paddy soil, oxidize soil organic matter, mix up and disturb soil biomes, destroy the habitats of many mesofauna, and create hardpans in paddies, all of which disrupt soil-mediated ecosystem services at the field and landscape levels [7,8]. Further, SRI does not maintain permanent cover on the soil with biomass materials as prescribed for CA. Rice monoculture leaves the ground bare between seasons and does not promote species diversity in rice paddies, which is a basic part of CA cropping and management.

Despite these differences, combining CA with elements of SRI is not only possible, but desirable. Table 1 reviews the basic elements of different strategies for crop management and notes the relationships among them, comparing methods for conventional rice cultivation (CRC) for irrigated or rainfed wetland cropping with SRI and CA production systems. The following sections consider in more detail the areas of compatibility and accommodation between the latter two systems that would facilitate synergistic benefits from their convergence.

Table 1. Comparisons among conventional (wetland) rice cultivation (CRC), SRI practices, and CA management (●●, Essential practice; ●, Compatible practice; P, Possible practice; and ×, Excluded practice).

Phases of Work	Principles	Practices	CRC	SRI	CA
Seed selection	Utilize best available genotypes	Selecting the best seeds to start with	●	●	●
Land/soil management	Prepare favorable soil environment for plant growth	Leveling of the field (a one-time operation)	●	●	●
	Avoid or minimize disturbance of the soil (CA)	Continuous no-tillage or minimum soil disruption	×	P	●●
		Construction of permanent raised beds (a one-time operation)	×	P	●
	Enhance soil fertility with increased organic matter (SRI and CA) + Permanent biomass soil cover (CA)	Adding organic matter to the soil	●	●●	●●
		Growing cover crops	×	P	●●
		Vegetative mulch cover	×	P	●●
Crop establishment	Establishment of healthy plants (CA + SRI)	Direct-seeding	●	P	●
		Transplanting young seedlings carefully	×	●●	P
	Minimize competition between plants (CA + SRI)	Wide spacing (at least 20 × 20 cm)	●	●●	●
	Crop diversification (CA)	Crop associations, e.g., intercropping, alley cropping, relay cropping, under-sowing	×	P	●
		Crop sequences and rotations	●	P	●●
Water management	Avoid flooding (hypoxic soil conditions) and minimize water stress (CA + SRI)	Maintaining mainly moist soil conditions, near field capacity	×	●●	●●
		Careful water control via irrigation	●	●●	●●
		Appropriate drainage systems and water capture (if rainfed)	●	●	●
Nutrient management		Organic inputs	●	●●	●
		Non-organic inputs	●	●	●
Weed control		Weed management with mulch, rather than with tools and/or herbicides	×	●	●●
		Use of soil-engaging mechanical weeder	×	●●	×
Pest and disease management		IPM + positive effects of CA and SRI + precise use of pesticides (organic or synthetic)	P	●	●
Crop biomass management		Retain above-ground crop biomass on the soil and root biomass in the soil	×	P	●●

2.1. *Avoiding Mechanical Soil Disturbance*

To benefit from CA, the preparation of fields should be carried out without disturbing the soil via tillage—or worse, by de-structuring the soil via the puddling of rice paddies.

Soil puddling, an almost universal practice for wetland rice cultivation [23], is not practiced in rice-based CA systems because it breaks up soil aggregates, destroying macropores in the soil, and impairs the micro-habitats of soil microorganisms. This degrades the biological, physical, chemical, and hydrological properties of the soil as well as its aeration and drainage [7,8]. Altering soil properties in this way adversely affects the functioning of food webs in the soil and diminishes the soil's provision of important ecosystem services [24].

One of the most common strategies to replace soil puddling is by practicing no-till, direct-seeded rice (DSR). This involves placing rice seeds directly into untilled soil rather than growing seedlings in nurseries and then transplanting them into puddled-flooded fields [25]. DSR can be conducted by drilling, single-grain precision-seeding of rice seeds into the soil, or by broadcasting them onto untilled soil, provided that the soil has enough moisture for germination. This method of rice crop establishment is consistent with the CA strategy and can be adapted for SRI management [26].

No-till DSR is consistent with SRI's emphasis on early and healthy plant establishment as there is no disturbance or trauma for the rice plant roots as happens with CRC transplanting. DSR systems have the potential to increase production and reduce plant lodging under adverse climatic conditions [27]. Compared to CRC transplanted rice, DSR can reduce the amount of labor required per season and it also lowers both water consumption and CH_4 emissions [28–31].

Coupling no-till DSR with the SRI principle of reducing plant density, to minimize plants' competition for water, nutrients, and sunlight, enables the development of larger canopies and deeper root systems. Rice plants with these phenotypic traits thrive in soils that are biologically active and have good structure and high levels of biomass carbon. Increasing the spacing between plants is conducted with CA because it is natural for tillering crops or non-tillering crops with bushy or spreading branching habits to grow more profusely in the more fertile soil environment that is created using CA practices [32]. Examples of ways to implement SRI principles without tillage can be seen in diverse parts of the world, using different kinds and degrees of mechanization as discussed in Section 3.

In lowland areas, CA promotes the system of permanent raised beds for growing irrigated or rainfed wetland rice without disturbing the soil (or disturbing it only once). Growing rice and other crops on raised beds with appropriate machinery facilitates the implementation of agronomic practices that are consistent with both SRI and CA systems on a large scale [12]. Soil compaction caused by the use of heavy machinery in fields can be avoided by constructing and spacing the raised beds so that tractor tires can drive along the furrows between the beds without disturbing the beds themselves. Compacting soil at the bottom of the furrows is beneficial since it makes for better lateral percolation of water into the beds themselves.

Forming raised beds initially requires a non-trivial expenditure of labor and/or capital (if construction is mechanized), but this is a one-time expenditure that leads subsequently to lower expenditure for both labor and fossil fuel. In the Pakistan (Figure 1) case, the formation of raised beds was found to cut the number of man-hours needed annually from 85 to 25 per hectare, a 70% reduction [12].

2.2. Water Management

With the water supply in many countries becoming scarcer or more unreliable, feeding future populations will also depend on increasing the efficiency and productivity of water use in rice cultivation. In a CA system, the management of water is similar to that in SRI, maintaining the soil in a mostly moist condition with no continuous inundation. In both CA and SRI, the aim is to nurture the abundance and diversity of soil organisms. Creating anaerobic soil conditions by flooding even one crop in a crop rotation will compromise the soil's structure and biota. Aerobic soil conditions, on the other hand, promote healthier, more active root systems, while also supporting more abundant communities of beneficial, mostly aerobic soil organisms [33].

Figure 1. Mechanized no-till DSR in Pakistan, on mulched raised beds with the PQNK system. Source: Pedaver Pvt. Ltd.

The larger, more robust root systems of CA crops and SRI-grown rice plants can better tolerate some water stress and they benefit from the absence of soil compaction and hard pans under CA management. Extended root systems are able to access water in lower soil profiles while reducing the lodging of plants by wind or rain due to stronger anchorage in the soil [34,35]. The combination of SRI and CA can increase benefits from more complex root systems that thrive in aerobic soil with increased moisture retention, resulting in a more efficient use of water and in greater resilience of all crop plants against water stresses. The two systems together increase the capture and availability of 'green water' and reduce reliance on 'blue water' (irrigation) [36].

The reduction in water requirements resulting from no longer keeping rice paddies flooded (SRI's water management practice) can be enhanced by the improved soil health environment that results from CA's crop, soil, and water management. Avoiding soil disturbance and increasing soil organic matter enhances the soil's infiltration and water-holding capacity, which permits longer periods between irrigation events and further reduces water needs [15].

Maintaining moist soil conditions in CA systems is conducted via water management with either drip irrigation or frequent irrigations (surface, subsurface, or overhead) or via cycles of AWD in surface (pulse-flood) irrigation, both of which can increase the water-use efficiency by more than 50% [33] and can lower emissions of CH_4 by 30–70% [37,38]. Reduction in CH_4 and N_2O emissions are attributable to improved soil drainage and aeration conditions as well as to the lower application of nitrogen fertilizers [32].

In rainfed lowland areas, which constitute ~30% of the world's wetland rice cultivated area, using SRI methods with appropriate adaptations offers a relevant option for raising the yield while making rice plants more resilient to water stress and reducing GHG emissions [39].

In low-lying fields with heavy clay soil, maintaining aerobic soil conditions in paddies can be difficult, and raised beds with furrows are the best or maybe only way to provide aerobic soil to rice plants and other crops in the cropping system. The provision of water through furrows laterally to the porous beds supplies sufficient water for plants' root systems to grow and acquire nutrients from a larger volume of soil. This economizes on irrigation water [12] and energy requirements. Where excessive rainwater stands on the field, this can be drained by the furrows to avoid unwanted flooding and its consequences [40].

Adaptations for water management in CA rice-based farming systems already include subsurface irrigation or intermittent surface and overhead irrigation with no standing water. Like the furrow irrigation system, these methods are compatible with the CA principles of minimum soil disturbance and maintaining permanent biomass mulch cover of the soil while producing the same benefits that accrue from avoiding hypoxic soil conditions.

2.3. Permanent Soil Cover

Both SRI and CA emphasize enrichment of the soil with organic matter. The CA principle of maintaining a permanent biomass soil cover does not present a challenge for a CA + SRI system, either in paddies or on raised beds. Under SRI management, however, organic matter is usually incorporated into the soil via mechanical disturbance which is not consistent with CA. A recommendation for maintaining permanent soil cover such as mulch is not, however, contrary to any of the SRI principles. Indeed, it is quite compatible with maintaining aerobic soil conditions.

In a CA-based rice system, the layer of mulch has to be thick enough to cover the soil surface (Figure 2) and prevent sunlight from reaching the soil, so that the germination of weeds is inhibited, which is a non-chemical strategy for weed control [41]. This interacts with the CA practices of no-till and crop diversification that contribute to reducing weed occurrence.

Figure 2. An example of mulched raised bed in Pakistan under the PQNK system. Source: Pedaver Pvt. Ltd.

CA is made more relevant for rice farming by the widespread practice of burning the rice crop's straw after harvest, with heavy environmental, economic, and health costs. This practice is prevalent in many parts of Asia, where 90% of the world's rice is produced, and especially where rice and wheat crops are alternated in the wet and dry seasons, as there is some urgency for getting rid of rice straw or using it quickly after the harvest. Every year, hundreds of millions of tons of rice straw are produced across Asia, a large proportion of which is burned, which impoverishes the soil, pollutes the air, and causes serious problems for human health [42].

Rice straw and stubble biomass are an abundant source of organic matter and burning them prevents the return of important elements to the soil, particularly sulfur (S), nitrogen (N), phosphorus (P), and carbon [43]. Shifting to CA + SRI makes the rice crop biomass a valuable source of plant nutrients and carbon, as well as a means for integrated weed, nutrient, and insect pest management. This gives farmers an economic incentive to stop burning their straw, which also improves air quality [42,44].

Maintaining permanent biomass cover on the soil surface protects the land from overheating in direct sunlight, which adversely affects much of the soil biota. Biomass cover also buffers the force of winds and storms that erode topsoil. As noted, it also reduces weed growth [41]. Further, by adding carbon and minerals to the soil system, it supports the proliferation of soil microorganisms and mesofauna [24], while also reducing rain runoff and evaporative losses of moisture [45]. The retention of non-harvested crop biomass, root stocks, and stubble in the field after harvesting enhances the stock of carbon in the soil; when these materials decompose, they support the soil biota and improve the structure and functioning of the soil.

Under SRI management, the production of rice straw is likely to exceed the amount needed to cover the soil surface as, according to several sources, SRI-grown rice plants produce a high quantity of biomass [46–49]. Also, tillering crops grow more profusely in the fertile soil environment created by CA practices [32]. For these reasons, CA + SRI systems should produce more than enough biomass to mulch the soil surface adequately, while also producing a surplus available for other uses, such as cattle fodder, bedding, or thatch.

Due to its high content of lignin and silica, rice straw is slow to decompose and remains for a longer time on the field surface than some other biomass [46]. Some studies have explored the possible allelopathic effects of rice plant biomass for inhibiting weeds. Although more research is needed to identify and test the various compounds that can affect weed growth, several studies have suggested that rice residues can be a source of natural herbicides [50–52]. The effectiveness of straw mulch for controlling weeds is of great importance in a production system where farmers may be concerned that the aerobic soil conditions and increased spacing between plants could encourage weed growth [41]. In certain cases, plastic films are being used in a CA + SRI system to cover the soil in raised beds mulched with biomass, as described by [40] and reported in Section 3.3. However, CA has a strong preference for vegetative ground cover, whether the plants are living or dead, so it does not encourage the use of plastic materials for mulch.

2.4. Diversification of the Cropping System

In CA + SRI systems, it is important to adopt strategies for achieving greater crop biodiversity in line with the CA principle of diversifying the cropping system. Diversification also contributes to permanent soil cover when farmers introduce cover crops between seasons or use crop associations such as intercropping, alley cropping, relay cropping, or under-sowing.

Agroforestry practices such as alley cropping, where trees are grown on agricultural fields, are one way to increase the availability of biomass and diversify plant species. CA-based perennial production systems such as orchards, plantations, and agroforestry can be found on all continents where agriculture is practiced. CA-based agroforestry and other perennial systems are feasible within irrigated-rice farming areas because of the aerobic soil conditions maintained during rice cultivation. Including trees in the cropping system also has other benefits such as increased biodiversity, greater land use efficiency, higher overall farm yield, enhanced carbon sequestration, and improved ecosystem services [53].

In CA + SRI cropping systems, integrating multi-purpose cover crops and/or green-manure cover crops (leguminous or not) into crop rotations or associations as practiced already in CA systems can add significant amounts of organic matter to the soil system, concurrently avoiding bare soil and enhancing biodiversity [24]. Cover crops used as green manures stabilize the soil moisture and temperature during the months when main crops are not being cultivated. This creates a favorable habitat for the soil biota that cycle biomass into humus and contribute to the stabilization of soil structure and function [54].

Crop associations, which are integral components of CA systems, are particularly common in most smallholder farming systems as species-diversification strategies for enhancing crop resilience to biotic and abiotic stresses as well as for enhancing overall land productivity [54]. Irrigated rice, on the other hand, is conventionally raised as a monoculture, in large part because the conventional practice of flooding rice fields does not offer suitable conditions for growing associated crops that cannot tolerate hypoxic soil. Under CA + SRI management, anaerobic soil conditions are avoided and the wider spacing between plants makes intercropping and other forms of mixed cropping more feasible. For example, combining pigeon pea and cowpea with irrigated rice production is reported to be a fairly common practice in Laos [54].

Systematic trials have been undertaken in the Anantnag District of Kashmir to evaluate the feasibility of intercropping mung beans (Vigna radiata) with rice cultivation under SRI management. These trials showed a significant decrease in weed prevalence and reduced irrigation needs, enhanced plant nutrient uptake, and higher yields. The research reported that, compared to monocultural SRI, the intercropping of leguminous mung beans led to an 8% increase in rice plants' nitrogen uptake and a 40% higher chlorophyll content in their leaves [55].

The effect on the SRI performance of intercropping mung beans with rice was substantial in these trials. A 20% increase in plant height was observed, for example, and the yield from rice intercropped with mung beans was 33% greater than from monocropped, flooded rice. With reduced costs of production (less expenditure on seed, water, and fertilizer), farmers' net income ha^{-1} was increased by 57%. The most visible effect of intercropping was an average 65% reduction in weed infestation over the two years of trials, comparing SRI fields with intercropping to SRI fields without intercropping and no weed management [55]. Practicing intercropping and other crop associations in a CA + SRI system could further reduce weed infestation by building on the effects of a permanent mulch layer, minimum soil disturbance, and longer-term reductions in the soil's store of weed seeds [41,56].

3. Some Examples

3.1. Pakistan

In the Punjab province of Pakistan, a private company (Pedaver Pvt. Ltd.) is working with tens of thousands of farmers in disseminating an agricultural system named PQNK (pronounced as 'picnic'). This is an acronym for Paedar Qudratti Nizam Kashatqari, which are Urdu words meaning 'sustainable farming system.' An earlier designation for PQNK was Paradoxical Agriculture [57]. Inspired initially by SRI principles and results, PQNK has developed into a methodology that combines SRI and CA principles and practices with organic farming as an overarching framework. With this methodology, shown in Figures 1–3, rice and other crops are cultivated on permanent, no-till, raised beds covered with biomass mulch, with irrigation applied in the furrows between beds instead of via flood irrigation [12].

Pedaver has developed machinery for transplanting young, single rice seedlings in the raised beds with precise spacing for a large-scale application of this methodology (the test plot was 8 hectares) [12]. On the same raised beds, other crops are then grown in rotation with rice following the crop management principles of SRI. This results in increased yields and greater income as well as in reduced water requirements and improved crop resilience [19]. Since starting his experimentation, Pedaver's founder, farmer–innovator Asif Sharif, has moved from transplanting to no-till direct-seeding (Figure 3). This further reduces labor and fuel requirements. In Pakistan, agricultural labor is costly, unavailable, or unreliable (crop planting is a time-sensitive operation). The methodology that Sharif developed has reduced water and labor requirements for rice cropping by 70%, with a yield of 12 tons ha^{-1} [12]. Other crops grown in rotation have been similarly successful [19].

Figure 3. Example of PQNK raised beds in Pakistan as described by [12].

3.2. USA

Adam Chappell is an innovative American farmer operating on over 3000 hectares of land, 20 miles southeast of Augusta, Arkansas. He has been using no-till, mulch cover, and crop rotation, including cover crops, since 2010. He has subsequently begun working with a combination of CA and SRI methods for the large-scale, mechanized rice-based production system that occupies part of his farm [58]. Chappell cultivates four crops in rotation (rice > cotton > corn > soy) and uses leguminous species, radishes, oats, and other plants as cover crops. As with the PQNK system, crops are planted on permanent no-till raised beds covered with vegetative material.

Chappell has made adjustments to a tractor-mounted seed-drilling implement to drill one or two rice seeds into the soil through the cover crops and crop biomass mulch at the desired shallow depth using air pressure. Chappell establishes two rows of rice plants, distanced around 40 cm apart, on each bed, maintaining 15 to 20 cm between the plants in each row, thus having 12–15 plants per m^{-2}. Water is provided to the crop through furrows 60 cm wide between the raised beds, which are each 50 cm wide. The beds and the furrows are completely covered by the plant canopies during the season once the plants have grown. Rice is harvested with a stripper-type combine that leaves the rice plants standing and it immediately drills the cover-crop seed right into the soil behind the combine. After the next rice crop is established, the seeder crimps or cuts the cover crop to create a mulch covering [59].

The combination of SRI crop management principles for rice cultivation with those of CA has allowed Chappell to grow rice on some areas of his farm where he could not grow rice before because the sandy-loam soil could not retain water and was therefore not suitable for flooding as prescribed for conventional rice management [60]. By maintaining his field soil under mostly aerobic conditions and nurturing the soil, Chappell is producing 7 to 9 tons of rice ha^{-1}, which is around the average among Arkansas rice farmers farming higher-quality soils and with much-reduced costs of production. The seeding rate is lowered from 28 kg ha^{-1} to around 5.5 kg ha^{-1}, which is the usual rate for SRI, and the use of synthetic fertilizers is significantly reduced. In this way, Chappell's rice production is more profitable than for most of the other rice farmers in the area [59]. This application of CA + SRI principles not only increases the economic returns from rice farming in Arkansas, but it also improves soil quality, cuts GHG emissions, and reduces reliance on purchased agrochemical inputs.

3.3. China

A six-year experiment was conducted by the Sichuan Academy of Agricultural Sciences using CA and SRI crop management on permanent no-till raised beds with plant biomass mulch and adapted SRI agronomic practices [40]. The practice of mulching is supplemented by covering the mulched surface with plastic film, which is usually not recommended with CA or SRI. The combination of organic and inorganic cover suppresses weeds quite thoroughly, solving the problem of weed competition with rice plants. In addition, it enhances soil moisture retention, supports soil mineralization, and inhibits insect pests and crop disease [40].

When rice is grown at higher elevations in Sichuan province where air temperatures are low, the plastic cover benefits the crop during its initial growing period by letting solar radiation through, trapping the heat generated and raising the soil temperature. Rice cropping in summer is rotated with rapeseed grown in the winter season. Its residue is put onto the raised beds as mulch for the rice crop and then rice straw is put on the beds after the grain is harvested.

These methods have achieved an 8% higher grain yield with the reduced use of N fertilizer, increased soil organic carbon, and greater resilience to drought. Of much interest, it was found that the use of plastic film was no longer needed after the fifth year. By this time, the combination of SRI crop management, no-till, and biomass mulching without any plastic cover on the raised beds achieved the highest yield of all the treatments evaluated [40].

A major drawback with this methodology was plastic pollution. The thin, cheap plastic with which farmers covered their raised beds was not reusable, so it was simply abandoned and blighted the environment. This problem could be dealt with by the use of heavier-gauge plastic which would be reusable. A longer-run solution will be to use plastic film that is biodegradable. This technology would achieve the beneficial effects of the current plastic film and then decompose [40,61].

3.4. Vietnam

As Vietnam's climate is too cold for rice cultivation between November and February, an experiment was conducted to evaluate the introduction of potato production as a winter crop between the spring and summer crops of rice [44]. In trials with 62 farmers, researchers from Thai Nguyen University found that combining SRI methods for more productive rice cultivation with no-till potato cropping for added income could increase farmers' income per labor-day three-fold compared to what they earned from conventional production of two rice monocrops a year.

The enhanced income results in part from the synergies that occurred between SRI and CA systems. Aerobic soil conditions during rice cropping made the soil better suited for no-till potato production; the winter potato crop broke the life cycle of rice pests such as the brown planthopper; and SRI rice plants produced abundant straw so that potatoes could be planted under the straw mulch rather than being dug into the ground, as is usual practice. This new practice saves farmers labor during both planting and harvesting. All in all, there were multiple benefits from modifying the monocultural rice cropping system and introducing SRI and CA practices [44].

3.5. Other Examples

Studies have been conducted in South Korea to determine the optimal rice plant spacing in no-till SRI rice cropping with a mulch soil cover of Chinese milk vetch (*Astragalus sinicus*) biomass. This cropping system was found to increase rice grain yield by 10%, with reduced inputs of labor, seeds, water, and agrochemicals compared to conventional rice farming methods in Korea [62,63]. The studies concluded that SRI methods integrated with no-till land management and Chinese milk vetch mulch cover were a desirable option for sustainably intensifying the farming systems of small-scale rice farmers in Korea, especially given the expected increased scarcity of irrigation water due to climate change.

In Maharashtra, India, the Saguna Rice Technique developed by the Saguna Rural Foundation has evolved into what it calls the Saguna Regenerative Technique, having the same acronym (SRT) while expanding its principles. SRT now combines CA principles with some SRI principles, promoting DSR on no-till raised beds with a wider spacing of plants (around 25 × 25 cm), crop rotation, avoiding flooded conditions, and retention of crop biomass on the soil surface [64]. Farmers adopting SRT methods rely on both chemical means of weed control and organic means for soil enrichment. These methods when disseminated among small-scale farmers in the Satar district of Maharashtra by the National Food Security Mission resulted in a yield improvement of around 20% as well as lower costs [65].

A merger of CA and SRI systems was initiated in 2011 in Madagascar by the Aga Khan Foundation and later replicated in India [14]. More recently, the Foundation has developed in Madagascar and then promoted in Mozambique, India, Kenya, and Tanzania an innovative package of sustainable agriculture techniques that it calls the Zanatany System or the Zanatany Rice Permaculture System (ZRPS). This is based on the direct seeding of rice combined with the local production and use of 100% natural inputs for soil fertility and crop protection, overlapping crop rotations, permanent soil cover, fodder compensation, minimum soil disturbance, and three practices in common with SRI: reduced plant density, aerobic soil conditions, and increased soil organic matter [66].

In North Korea, CA has been introduced in some rice-growing areas, accompanied by the gradual adoption of SRI agronomy, drastically reducing the plant densities. Reduction in seed rates is common with CA crops and cropping systems, including in rice-based CA systems, because of improved soil conditions, more uniform seeding, and higher germination rates. At the same time, some farmers have started rotating the growing of rice on permanent wide beds with a rotation of no-till mulched potatoes similar to what is described above in the Vietnam case [67]. In the DPRK, these practices have received government endorsement and support.

4. Conclusions

The urgency to reduce the adverse environmental impacts of food production, particularly GHG emissions, is more pressing than ever, and revising methods for rice farming is an opportunity both to increase staple food production and contribute to abating the acceleration of climate change. Capitalizing on the synergies of agroecological practices could help address the negative externalities of rice farming while increasing crop resilience against the effects of climate change.

CA-based rice cropping systems are already being practiced in some countries either in paddies or in raised beds with furrow irrigation. SRI crop management can be adapted to converge with CA so that the rice production entails little or no soil disturbance; has permanent biomass mulch covering of the soil; crop diversification; maintains mostly aerobic soil conditions; and optimizes spacing between plants for greater growth of roots and tillers. The specific practices need, of course, to be adapted to the local contexts as is always recommended with both CA and SRI.

CA and SRI methods have already been successfully combined in several areas of the world as diverse as Pakistan, USA, and China, so that converging the two systems with appropriate adaptation is feasible and attractive for farmers. The adoption of CA by SRI farmers and rice farmers in general can benefit a wide constituency of farmers worldwide, particularly smallholders but also large-scale farmers with suitable mechanization. Governments of rice-producing countries should consider rewarding farmers who grow rice by combining CA and SRI methods because of the positive externalities of these approaches. Also, as CA + SRI systems are knowledge-intensive rather than resource-intensive, informed extension services should be in place and able to work collaboratively with farmers to develop specific practices suited to the context. The uptake and further adaptation of SRI crop management with CA systems will, to be sure, benefit from additional research on the effects of combining these approaches, thereby increasing our understanding of regenerative natural processes and how they can be harnessed to support more sustainable and resilient food production.

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