Stimulating Ecological Intensification of Cropping Systems in Nigeria – Short-Term Impact of Ecological Cropping Systems on Maize Productivity, Weed Management, Soil Health, and Nitrogen Fertilizer Economy

Anthony Oyeogbe [1,*]

[1]*University of Ibadan; ai.oyeogbe@ui.edu.ng*
**Correspondence: ai.oyeogbe@ui.edu.ng*

Citation: Oyeogbe A. (2023) Stimulating Ecological Intensification of Cropping Systems in Nigeria – Short-Term Impact of Ecological Cropping Systems on Maize Productivity, Weed Management, Soil Health, and Nitrogen Fertilizer Economy. FARA Research Report *Vol 7(73):948-957*.
https://doi.org/10.59101/frr072373

Abstract:

Conventional cropping practices (CP) have adversely impacted soil health. A shift to ecological intensification practices can sustain the soil ecosystem services. Conservation agriculture (CA), organic agriculture (OA), and regenerative agriculture (RA) are paradigms of ecological intensification. This study examined the impacts of CP, CA, OA, and RA on maize yields, weed management, soil health, and nitrogen (N) fertilizer economy. In the first year of cropping, maize yields under CP and CA increased significantly by 24 – 31 % compared to OA and RA. Weed growth reduced significantly in CP and CA in the early stage (21 days after maize sowing) compared to OA and RA but increased in CP than CA at the late stage of maize growth (49 days after maize sowing). OA and RA marginally increased the soil organic matter (SOM), but total N and phosphorus (P) concentrations in soil were slightly higher in the CA and CP systems. Also, CA used 25 % less N fertilizer dose in providing similar yields with CP. Transitioning to CA contributes to maize yield increase, soil fertility, and weed management. Nurturing ecological cropping systems in the long-term can reduce mineral N fertilizer input in CA while sustaining yields and enhancing ecosystem services.

Keywords: African smallholder cropping, agroecology, ecosystem services, nature-based cropping.

---

1. Introduction

The intensive tillage, synthetic fertilizers, and pesticides are conventional cropping practices to achieve high yields. Yet, maize yields have not increased significantly under the conventional cropping, particularly in smallholder systems across Africa [1-4]. Moreover, continuous tillage and excessive agrochemical inputs are detrimental to the environment and human wellbeing [5]. Shifting from conventional to alternative (nature-based) cropping would require implementing ecological practices that can sustain or increase yields while restoring soil health and protecting the environment [6-9]. Ecological cropping systems are resource-efficient crop production systems based on integrated management of soil, water, and biological resources [10]. Although ecological cropping systems present several tradeoffs [1], such as yield decline, nitrogen immobilization, and weed proliferation in the early years of implementation [11-12], these can be surmounted in the long term or after the system has fully stabilized. Integrating adaptive agronomic practices such as site-specific precision nutrients and integrated weed management can alleviate the tradeoffs in the early conversion period [11,12].

Ecological intensification has gain scientific and policy attention concerning sustainable food systems, ecosystem services, and biodiversity conservation [1,8,9,13]. Ecological intensification is defined as the enhancement of ecosystem services to complement or substitute for the role of anthropogenic inputs in maintaining or increasing yields [1,8–10]. Paradigms of ecological intensification practices include minimum soil disturbance through zero tillage; continuous soil cover with crop residue mulch; diverse crop rotations, intercrops, and polycultures, green fertilization from organic and plant manure [1,10]. Ecological intensification practices are practical tenets embedded in conservation agriculture (CA), organic agriculture (CA), and regenerative agriculture (RA), which have shown to enhance agricultural and environmental benefits. Although CA permits synthetic fertilizer and herbicide inputs, particularly during the early years of implementation, to stabilize the system [14], OA allows conservative soil tillage to reduce weed growth [15]. Using long-term experiments across Africa and Europe, [13] reveals that ecological intensification practices can reduce the need for anthropogenic inputs (continuous tillage, synthetic fertilizer, and pesticide) to achieve high yields. They demonstrated that combining an appropriate mix of ecological intensification practices with significantly less synthetic N fertilizer could provide the same yields as conventional practice with high-input synthetic N fertilizer.

In Africa, CA implementation has attained widespread adoption [16], while OA lacks effectiveness, and RA is at the early stages of research. A global analysis of CA showed that maize yield increased by 10-20 % when N fertilizer application increased from 40 to 80 kg N ha^{-1} in diverse smallholder systems across Africa [3,4]. [13] indicate the optimal mineral N fertilizer rate to sustain crop yields under ecological cropping practices should be around 100 kg ha^{-1} N or less with the addition of legume and organic manure. An increase in fertilizer application would require substantial investment by the poor-resource smallholder farmers in Africa [16, 17]. Alternative ecological cropping systems that harness plant and animal manures and crop residues to maintain soil fertility and sustain crop yields would require substantial research in smallholder systems to understand tradeoffs, conflicts, and benefits of agroecosystem sustainability.

To my knowledge, no study has evaluated the impact of the conventional and ecological systems (conservation agriculture, organic agriculture, and regenerative agriculture systems) together in a single study. Leapfrogging to ecologically cropping systems can contribute to the productivity and sustainability of African smallholder cropping systems. In addressing the knowledge gap, the overarching objective of this study is to identify suitable ecological cropping systems for smallholder maize systems that can sustain or increase crop yields and soil fertility and reduce weed growth. The hypotheses of this study are 1). CP cropping would increase maize yields compared to CA, OA, and RA; 2). CA, OA, and RA practices would provide a more effective weed control comparable to CA; and 3). CA, OA, and RA with cover crop would enhance the soil fertility compared to CP. The ecology and economic balance of N fertilizer and herbicide use implications in CA related to productivity and sustainability are enumerated.

2. Materials and Methods

2.1 Study site description

The experiment in the University of Ibadan Agronomy Research Farm (7°27′06′′N 3°53′26′′E; 195 m asl) in Ibadan, Southwestern Nigeria, was conducted during the 2021 rainy season (April - Aug). The field has a sandy loam soil texture, which is well drained, non-calcareous, and slightly acidic (pH of 6.4), classified under the group of Alfisols according to the US Taxonomy. The climate is sub-tropical, average annual rainfall of 1100 mm in the last five years. About 60 % of the annual rainfall occurs during April–August when maize is grown. The mean monthly temperatures during the growing season varied from 26.8 to 31.6 °C. The experimental field has been under conventional practices before this study. At the commencement of this experimentation, the total N and soil available P and K concentrations in the 0-0.15 m depth was analyse to determine nutrient availability or deficiency. Total N in soil was determine by the Kjeldahl method, and N concentration (1.3 g kg^{-1}) was below critical limit of 1.5 g kg^{-1}, while the concentration of available P (16 mg kg^{-1}) and K (0.03 cmol kg^{-1}) were estimate by Bray P and flame photometer methods, respectively, and were above their critical limits of 15 mg kg^{-1}, and 0.15 cmol kg^{-1}, respectively. In this study, mineral N fertilizer was added to optimize the soil N for sustaining maize yields to cropping systems where necessary. Details of mineral N fertilizer are described under agronomic management.

2.2 Experimental details

The field was layout in a randomized block design with four cropping systems management with four replications. The experiment plot size of each cropping system management was 4.5 m by 3.0 m. The four cropping systems management are conventional practice (CP), conservation agriculture (CA), organic agriculture (OA), and regenerative agriculture (RA).

2.3 Agronomic management

Hybrid maize (var. Oba Super 6) sourced from the International Institute of Tropical Agriculture (IITA), Ibadan, was sown at the rate of 20 kg ha^{-1} in May, 5 2021. Prior to maize sowing, cowpea (local var. Ife brown) cover crop under CA, OA and RA systems was sown ten days earlier than maize at the rate of 20 kg ha^{-1} (75 × 25 cm row spacing). Tillage operation under CP and OA was performed with a hand-hoe two days before maize sowing. A pre-emergence selective herbicide (atrazine at the rate of 2 kg a.i ha^{-1}) under CP and CA systems was applied two days after maize sowing. Organic manure with poultry and cow dung at 5 t ha^{-1} (2.5 t each) was added in OA and RA systems ten days before maize sowing. Mineral N fertilizer from urea was added in the CP and CA system using the standard 'smallholder' dose of between 20-60 kg N ha^{-1} for maize in Nigeria. Under CP cropping, 60 kg N ha was applied in two splits of 30 kg N ha^{-1} each at the onset of maize sowing and 30 days after, whereas 40 kg N ha was applied in CA in two splits of 20 kg N ha^{-1} each at the onset of maize sowing and 30 days after. The reduction of N fertilization in CA was to evaluate yield-related productivity with minimal mineral N use. The legume cover cropping under CA, OA and RA was terminated after 30 days of growth but 20 days as intercrop with maize sowing and placed on the soil surface as crop residue mulch for weed suppression and soil N fertility management. A simplified version of the cropping system philosophies are described in Table 1.

Table 1. Maize cropping system management practices.

Conventional and ecological cropping systems philosophies and description
1. Conventional cropping practice (CP): includes tillage, fertilizer and herbicide inputs.
2. Conservation agriculture (CA): includes zero-tillage, cover crop residue, and fertilizer and herbicide inputs.
3. Organic agriculture (OA): includes tillage, cover crop residue and organic manure inputs.
4. Regenerative agriculture (RA): includes zero-tillage, cover crop residue, and organic manure inputs.

2.4 Maize yields and weed population measurement

Maize grain and stover yields were harvested at the physiological maturity stage (95 days after sowing). The maize grain yield was reported at 15 % moisture content and expressed in t ha^{-1}. Stover (biomass) yields was weighed after two weeks of sun-drying on the field in t ha^{-1}. Weed populations at 21 and 49 DAS were assessed by randomly placing a quadrat of size 0.5 m × 0.5 m (0.25 m^{-2}) in each plot. The weeds were oven-dried at 65 °C till constant weight. Weed density and dry weight of its biomass were express in no. m^{-2} and g m^{-2}, respectively.

2.5 Soil analysis

After maize harvest, soil samples in 0 – 0.15 m depth was obtain from the experimental plots in various cropping systems management. The soils were air-dried, crushed, and sieved with 2 mm mesh for total N, available N and P analyses, and 0.5 mm for the organic carbon estimation. Total N (g kg^{-1}) in soil was estimated using the Kjeldahl digestion method, while soil available P and K (mg kg^{-1}) were analyze with the Bray P method and flame photometer, respectively. Soil organic carbon (%) was estimated using the wet oxidation method, which was converted to derived organic matter using the van Bemmelen conversion factor of 1.724 (i.e., % organic carbon in soil × 1.724).

2.6 Statistical analysis

Data were subject to analysis of variance (ANOVA) for the randomized block design using the SAS package 9.1 (SAS Institute, Cary, NC). Considering the non-normality distribution of weed density and dry weight, their data was transform by the square-root method ($\sqrt{x+0.5}$) to satisfy conditions for the analysis of variance comparison. Where cropping systems effect was significant at $P \leq 0.05$, LSD comparisons of means is use as a posthoc test. P values between 0.05 and 0.10 were considered marginally significant.

3. Results

3.1 Maize yields

Maize grain and biomass (stover) yields was significantly different ($p = 0.05$) among the cropping systems (Table 2). Grain yield of maize increased by 27-31 % in the CP (3.69 t ha^{-1}) and 24-27 % in CA (3.51 t ha^{-1}) compared to OA (2.68 t ha^{-1}) and RA (2.55 t ha^{-1}), respectively. Also, biomass yields increased significantly in the CP (4.81 t ha^{-1}) and CA (4.49 t ha^{-1}), respectively compared to RA (3.21 t ha^{-1}) and OA (3.03 t ha^{-1}).

Table 2. Maize yields as affected by cropping systems management.

Cropping systems management	Grain yield	Stover yield
	t ha^{-1}	
Conventional practice (CP)	3.69a	4.81a
Conservation agriculture (CA)	3.51a	4.49a
Organic agriculture (OA)	2.68b	3.21b
Regenerative agriculture (RA)	2.55b	3.03b
SEm	0.23	0.29

Means with different letter in the same column under respective cropping system management are significantly different based on LSD ($P \leq 0.05$).
SEm, Standard error of mean.

3.2 Weed density and biomass

Weed density and biomass were significantly different ($p = 0.05$) among the cropping systems (Table 3). In the early growth stage of maize (21 days after sowing), weed density (no. m^{-2}) decreased significantly in CP (28) and CA (35) compared to OA (68) and RA (91) systems, but increased significantly in CP (49) than CA (44) system during maize development stage (49 days after sowing). Also, weed biomass (g m^{-2}) decreased significantly in CP (6.5) and CA (9.1) compared to OA (38.5) and RA (42.7) systems, but increased significantly in CP (29.5) than CA (18.8) system during maize development stage (49 days after sowing).

Table 3. Weed density and biomass as affected by cropping systems management.

Cropping systems management	Weed density		Weed biomass	
	no m^{-2}		g m^{-2}	
	21 DAS	49 DAS	21 DAS	49 DAS
Conventional practice (CP)	28 (5.3)a	49 (7.0)b	6.5 (2.6)a	29.5 (5.8)b
Conservation agriculture (CA)	35 (5.7)a	44 (6.4)a	9.1 (3.0)a	18.8 (4.2)a
Organic agriculture (OA)	68 (8.1)b	79 (8.9)c	38.5 (6.1)b	49.4 (7.0)c
Regenerative agriculture (RA)	91 (8.5)c	104 (10.0)d	42.7 (6.4)b	52.6 (7.2)c
SEm	0.38	0.28	0.42	0.34

Means with different letter in the same column under respective cropping system management are significantly different based on LSD ($P \leq 0.05$). SEm, Standard error of mean.

3.3 Soil organic matter and nutrient concentrations

The soil organic matter (SOM) and available N and P concentrations after maize harvest was marginally significant (p = 0.07; 0.08, 0.10 respectively) among the cropping systems (Table 4). SOM concentration increased slightly in RA (2.2 %) and OA (2.2 %) compared to CA (1.9 %) and CP (1.6 %), while total nitrogen (N) and available phosphorus (P) in soil were slightly higher in CP (1.9 g kg^{-1} and 28 mg kg^{-1}) and CA (1.7 g kg^{-1} and 26 mg kg^{-1}) compared to OA (1.6 g kg^{-1} and 22 mg kg^{-1}) and RA (1.6 g kg^{-1} and 23 mg kg^{-1}). Available potassium (K) in soil remain the same.

Table 4. Soil organic matter (SOM) and available N and P concentrations at 0–0.15 m depth as affected by cropping systems management.

Cropping systems management	SOM (%)	Total N (g kg^{-1})	Available P (mg kg^{-1})	Available K (cmol kg^{-1})
Conventional practice (CP)	1.6c	1.9a	28a	0.3a
Conservation agriculture (CA)	1.9b	1.7ab	26a	0.4a
Organic agriculture (OA)	2.2a	1.6b	22b	0.4a
Regenerative agriculture (RA)	2.2a	1.6b	23b	0.3a
SEm	0.07	0.09	0.04	0.03

Means with different letter in the same column under respective cropping system management are significantly different based on LSD ($P \leq 0.05$).
SEm, Standard error of mean.

3.4 Nitrogen fertilizer economy

N fertilizer use efficiency increased in CA compared to CP. Fertilizer economy is the quantity of the N fertilizer saved in CA compared to CP. CA reduced N fertilizer application by 20 kg N ha^{-1}.

4. Discussion

The hypothesis that maize yields would increase in conventional (CP) agriculture practices compared to the ecological-based systems of CA, OA and RA is partly supported. Maize yields were greater under CA and CP than OA and RA, suggesting mineral N input contribution to maize yields. Many soils in Africa are N-limited and thus, require amendment either through mineral (synthetic) fertilizers or organic (natural) manures to enhance soil N availability for crop use and productivity [1]. In this study, mineral N fertilizer was included in CA as in the CP, while N supply in OA and RA came from organic manures and crop residues. [13] demonstrated that ecological intensification practices could support the use of synthetic N fertilizer in sustaining yields in African smallholder systems where soil N is limited. Sufficient mineral N fertilizer addition in N-deficient soil under the CA maize system in Africa increases maize yields similar to CP [3,4]. Although the N fertilizer rate in CA was 20 kg N less than CP, the maize yields were comparable. [13] demonstrated that ecological intensification practices significantly increases yield at low N fertilizer doses but have minimal effect at high N fertilizer doses on yield. N fertilizer addition as a fourth principle in sustaining crop yield was suggested by [18]. [11,12] showed that adaptive N management in CA could maintain maize yields after two years of cropping.

Addition of organic N in OA and RA systems did not positively affect maize yields more than mineral N in CA. Ecological cropping systems of OA and RA systems rely on organic manures, cover crops, and crop residues for N supply to boost yields. N from organic manuring tends to remain unavailable for a long time [3,19], and thus, slow N release from manures may not contribute to maize yields increase in the current cropping season. Furthermore, soil tillage in OA did not significantly contribute to increasing maize yield than RA without tillage. [13] showed that ecological intensification practices provided similar effects with different tillage intensities and that increasing tillage did not strongly affect the crop yields. On the other hand, soil tillage in the OA system may contribute to a more positive effect on rapid organic manure turnover and nutrient availability for crop productivity, including soil carbon loss [20]. The intensification of ecological cropping systems for productivity-enhancing and resource-saving paradigms would require combining organic and inorganic N sources.

The hypothesis that CA, OA, and RA practices would provide effective weed suppression comparable to CA is partly supported. In the early period of maize growth, tillage and herbicide use under CP and herbicide and cover crop in CA provided more effective weed management than tillage in OA, suggesting that herbicide use was an important contribution to weed suppression. In the advanced stage of maize development, cover crop residues on the soil surface and the residual effect of herbicide under CA smother weed growth than herbicide residues effects alone in CP. In this study, herbicide use and legume cover crop residues showed higher weed suppression effect at the critical stage of weed-maize competition than the tillage. Effective weed management during the critical period of weed competition with maize (15-40 days of maize sowing) is crucial to reducing yield penalties. These results suggest that weed suppression through cover crop residues increases with time while the herbicide efficacy declines over time. Therefore, in the early transition periods, herbicide use in ecological cropping systems can provide a more effective and immediate strategy in managing the large weed seed bank in the soil, while the cover crop residues can sustain weed suppression in reducing yield penalties [21,22].

In addition to weed suppression, cover crop mulching support several ecological services, such as enhanced nutrient transformation, and reduced soil erosion and N loss [23-25]. Determining the appropriate level of cover crop biomass for weed suppression, coupled with the right termination timing of the cover crop is critical to protecting crop yields [24-26]. Integrated weed management with tillage, herbicide, and cover crop residues inputs are silver bullets that can reduce the weed seed bank in soil (including both true seeds and vegetative propagules of perennial weeds). [11,12] demonstrated that integration of herbicide mixtures and brown manuring suppresses weed growth more than herbicide mixtures alone in maize-wheat systems under CA after two years of cropping. More importantly, new technologies in harvest weed seed reduction are expanding opportunities to manage the seed bank [27-29].

The hypothesis that CA, OA, and RA systems would enhance SOM and available nutrients compared to CP is partly supported. The SOM was greater under OA and RA and in CA with mineral N fertilizer, suggesting that the legume cover crop residue was the main contribution to organic matter. Yet, SOM accumulation was slightly higher in OA and RA than in CA. This result suggests that organic manure addition strongly influenced the SOM concentration than the legume cover crop residues. Cover cropping and organic manuring are ecological intensification practices in restoring soil health. Legumes are biological nitrogen fixers capable of enhancing the soil N economy in cropping systems through microbial activity [30,31]. Increased microbial activities in the soil would influence the rapid turnover of organic manure and crop residues into organic matter [30,31].

On the other hand, total N and available P in the soil slightly increased in CP and CA, suggesting that organic manuring and cover cropping in OA and RA had minimal effect. The soil total N and available P was slightly higher in CA without organic manure, suggesting that mineral N fertilizer addition was the main contribution to nutrient availability [32]. However, [33] indicated that mineral N fertilizer with organic manure and not legume increases nutrient availability such as P and K and their release. In this study, organic manures and legume cover crops may have influenced microbial N immobilization in soil, indicating reduced N availability for crop uptake [30–32,34]. N supply from organic manures and crop residues tend to remain inaccessible for a long time [3,34,35], [32,35] indicated that mineral N fertilizer addition would provide the soil microbial N requirement responsible for the rapid turnover of available nutrients. Integrating mineral N fertilizer with organic manure and legume cover crop residues can provide sufficient N for microbes and crop requirements [30-32]. Although organic manuring may have provided only a small positive effect on soil total N and available P concentrations in the first year of maize cropping, a legacy or residual N and P effect on available N and P is expected in the subsequent cropping seasons/years [36,37]. Therefore, combining mineral and organic N sources can provide a more effective strategy for enhancing soil N fertility in ecological cropping systems in both the short- and long-term.

Balancing productivity and ecology: N fertilizer and herbicide addition

Since the Green Revolution, fertilizer and herbicide use in conventional cropping systems has provided much-needed productivity gains and food security, but intensive over-use has caused substantial environmental damage [5]. For a shift to an ecological cropping system that can ensure agroecosystem sustainability, depleted soil N and weed seed bank pressure must be addressed, particularly in African smallholder cropping systems [11,12]. In this study, N fertilizer and herbicide inputs under CA contributed to higher maize productivity in the first year of implementation. Significantly, the yield-related productivity of maize increased with N fertilizer under CA compared to CP. N fertilizer economy in CA (40 kg N ha^{-1}) was 25 % less than in CP (60 kg N ha^{-1}). High-input synthetic N fertilizer under ecological cropping increases the environmentally-damaging effect while reducing yield-related productivity [23].

Managing an ecological cropping system to sustain productivity that provides numerous ecosystem services can encourage farmers to shift to environmentally-friendly practices. For ecological cropping systems where soil N availability is low, particularly in smallholder cropping, the inclusion of mineral N fertilizer can influence yields. Likewise, reducing mineral N fertilizer in the ecological cropping system will ensure agroecosystem sustainability. Ecological intensification of the cropping system is sustained by nature and sustainable in itself [10]. In this study, the inclusion of legume cover crop and organic manure in the nature-based systems of CA, OA, and RA, contribute to sustaining soil N availability, weed suppression, and maize yields, thereby reducing the need for high inputs of mineral N fertilization and herbicide. These ecological cropping systems can support the redistribution of synthetic N fertilizer use by enhancing yields if combined with modest fertilizer inputs.

Furthermore, social, economic, and environmental performances of conventional and ecological cropping systems should be evaluated when both systems have attained their stability (habitually practiced for the same number of years concerning their tenets/philosophies). Implementing ecological intensification practices in cropping systems requires a few years to stabilize, and only then will the comparison with conventional cropping practices be balanced.

Author Contributions: Conceptualization, A.I.O. methodology, A.I.O. software, A.I.O. validation, A.I.O. formal analysis, A.I.O. investigation, A.I.O. resources, A.I.O. data curation, A.I.O. writing—original draft preparation, A.I.O. writing—review and editing, A.I.O. visualization, A.I.O. supervision, A.I.O. project administration, A.I.O.
Funding: This research received no external funding.
Institutional Review Board Statement: Not applicable.
Informed Consent Statement: Not applicable.
Data Availability Statement: Not applicable.
Conflicts of Interest: The authors declare no conflict of interest.

References

1. Tittonell, P.; Giller, K. E. When yield gaps are poverty traps: the paradigm of ecological intensification in African smallholder agriculture. *Field Crops Res*. **2013**, 143, 76–90.
2. Thierfelder, C.; Baudron, F.; Setimela, P.; Nyagumbo, I.; Mupangwa, W.; Mhlanga.; Lee, N.; Gérard, B. Complementary practices supporting conservation agriculture in southern Africa. A review. *Agron. Sustain. Dev*. **2018**, 38, 16–37.
3. Lundy, M.E.; Pittelkow, C.M.; Linquist, B.A.; Liang, X.; Van Groenigen, K.J.; Lee, J.; Six, J.; Venterea, R.T.; Van Kessel, C. Nitrogen fertilizer application reduces yield declines following no-till adoption. *Field Crops Res*. **2015**, 83, 204–210.
4. Pittelkow, C.M.; Linquist, B.A.; Lundy, M.E; Liang, X.; Van Groenigen, K.J.; Lee, J.; Vangestel, N.; Six, J.; Venterea, R.T.; Van Kessel, C. When does no-till yield more? A global meta-analysis. *Field Crops Res*. **2015**, 183, 156–168.
5. Pingali, P. L. Green revolution: impacts, limits, and the path ahead. *Proc. Natl Acad. Sci*. **2012**, 109, 12302–12308.
6. Steffen, W.; Johan, R:, Rockström, J:, Cornell, S.E.; Fetzer, I.; Bennett, E.M.; Reinette, B.; Carpenter, S.R.; De Vries, W.; Dewit, C.A:, Folke, C.; Gerten, D.; Heinke, J:, Mace, G.M.; Persson, L.M.; Vramanathan, V.; Reyers, B.; Sörlin, S.; Planetary boundaries: guiding human development on a changing planet. *Sci.* **2015**, 347, 1259855.
7. Springmann, M.; Clark, M.; Mason-D'Croz, D.; Wiebe, K.; Bodirsky B.L.; Lassaletta, L.; De Vries, W.; Vermeulen, S.J; Herrero, M.; Carlson, K.M; Jonell, M.; Troell, M.; DeClerck, F.; Gordon, L.J.; Zurayk, R.; Scarborough, P.; Rayner, M.; Loken, B.; Fanzo, J.; Godfray, H.C.J.; Tilman, D.; Rockström, J.; Willett, W. Options for keeping the food system within environmental limits. *Nat.* **2018**, 562, 519–525
8. Bommarco, R.; Kleijn, D.; Potts, S. G. Ecological intensification: harnessing ecosystem services for food security. *Trends Ecol. Evol*. **2013**. 28, 230–238.
9. Kleijn, D. Bommarco, R.; Fijen, T.P.M.; Garibaldi, L.A.; Potts, S.G.; van der Putten, W.H. Ecological intensification: bridging the gap between science and practice. *Trends Ecol. Evol*. **2018**, 34, 154–166.
10. Tittonell, P. Ecological intensification of agriculture–sustainable by nature. Curr. Opin. *Environ. Sustain*. **2014**, 8, 53–61.
11. Oyeogbe, A.I.; Das, T.K.; Bandyopadhyay, K.K. Agronomic productivity, nitrogen fertilizer savings and soil organic carbon in conservation agri¬culture: Efficient nitrogen and weed management in maize-wheat system. *Arch. Agron. Soil Sci*. **2018**, 1635-1645.

12. Oyeogbe, A.I.; Das, T.K.; Bhatia, A.; Singh, S.B. 2017. Adaptive nitrogen and integrated weed management in conservation agriculture: impacts on agronomic productivity, greenhouse gas emissions and herbicide residues. *Environ. Monitor. Assess*. **2017**, 189(4):198.
13. MacLaren, C.; Mead, A.; van Balen, D.; Claessens, L.; Etana, A.; de Haan, J.; Haagsma, W.; Jäck, O.; Keller, T.; Labuschagne, J.; Myrbeck, J.; Necpalova, M.; Nziguheba, M.; Six, J.; Strauss, J.; Swanepoel, P.A.; Thierfelder, C.; Topp, C.; Tshuma, F.; Verstegen, H.; Walker, R.; Watson, C.; Wesselink, M.; Storkey, J. Long-term evidence for ecological intensification as a pathway to sustainable agriculture. *Nat Sustain*. **2022**.
14. Food and Agriculture Organization (FAO). Conservation agriculture. Available online: http://www.fao.org/ag/ca/. Basic principles of conservation agriculture (accessed 10 August 2022).
15. International Federation of Organic Agriculture Movements (IFOAM). The four basic principle of organic agriculture https://www.ifoam.bio/why-organic/shaping-agriculture/four-principles-organic (accessed 10 August 2022).
16. Rusere, F.; Crespo, O.; Dicks, L.; Mkuhlani, S.; Francis, J.; Zhou, L Enabling acceptance and use of ecological intensification options through engaging smallholder farmers in semi-arid rural Limpopo and Eastern Cape, South Africa. *Agroecol. Sust. Food Syst*. **2020**, 44:6, 696-725.
17. Giller, K. E. The food security conundrum of sub-Saharan Africa. *Glob. Food Sec*. **2020**, 26, 100431.
18. Vanlauwe, B.;Wendt, J.; Giller, K.E; Corbeels, M.; Gerard, B.; Nolte, C. A fourth principle is required to define conservation agriculture in sub-Saharan Africa: the appropriate use of fertiliser to enhance crop productivity. *Field Crops Res*. **2014**, 155, 10–13.
19. Chivenge, P. Vanlauwe, B.; Gentile, R; Six, J. Comparison of organic versus mineral resource effects on short-term aggregate carbon and nitrogen dynamics in a sandy soil versus a fine textured soil. *Agric. Ecosys. Environ*. **2011**, 140, 361–371.
20. Lal, R. Carbon emission from farm operations. *Environ. Int*. **2004**, 30, 981–990.
21. Nichols, V.; Verhulst, N.; Cox, R.; Govaerts, B. Weed dynamics and conservation agriculture principles: a review. *Field Crops Res*. **2015**, 183, 56–68.
22. Farooq, M.; Flower, K.C.; Jabran, K.; Wahid, A.; Siddique, K.H.M. Crop yield and weed management in rainfed conservation agriculture. *Soil Tillage Res*. **2011**, 117, 172–183.
23. Mhlanga, B.; Ercoli, L.; Pellegrino, E.; Onofri, A.; Thierfelder, C. The crucial role of mulch to enhance the stability and resilience of cropping systems in southern Africa. **Agron. Sustain. Dev**. **2021**, 41, 29–43.
24. Osipitan, O. A.; Dille, J. A.; Assefa, Y.; Knezevic, S. Z. Cover crop for early season weed suppression in crops: systematic review and meta-analysis. *Agron. J*. **2018**. 110, 2211–2221.
25. Osipitan, O. A.; Dille, J. A.; Assefa, Y.; Radicetti, E.; Ayeni, A.; Knezevic, S. Z. Impact of cover crop management on level of weed suppression: a meta-analysis. *Crop Sci*. **2019**, 59, 833–842.
26. Schwartz-Lazaro, L.M.; Gage, K.L.; Chauhan, B.S. Editorial: Weed Biology and Ecology in Agroecosystems. *Front. Agron*. **2021**, 3, 730074.
27. Schwartz-Lazaro, L. M.; Norsworthy, J. K.; Walsh, M. J.; Bagavathiannan, M. V. Efficacy of the integrated harrington seed destructor on weeds of soybean and rice production systems in the Southern United States. *Crop Sci*. **2017**, 57, 2812–2818.
28. Shergill, L. S.; Schwartz-Lazaro, L. M.; Leon, R.; Ackroyd, V. J.; Flessner, M. L.; Bagavathiannan, M., Everman , W.; Norsworthy , J.K.; VanGessel, M.J.; Mirsky, S.B. Current outlook and future research needs for harvest weed seed control in North American cropping systems. *Pest Manag. Sci*. **2020**, 76, 3887–3895.
29. Walsh, M. J.; Broster, J. C.; Schwartz-Lazaro, L.M.; Norsworthy, J. K.; Davis, A. S.; Tidemann, B. D.; Beckie , H.J.; Lyon, D.J.; Soni, N.; Neve , P.; Bagavathiannan, M.V. Opportunities and challenges for harvest weed seed control in global cropping systems. *Pest Manag. Sci*. **2018**, 74, 2235–2245.
30. Kumar, S.; Meena, R.S.; Singh, R.K.; Munir, T.M.; Datta, R.; Danish, S.; Yadav, G.S.; Kumar, S. Soil microbial and nutrient dynamics under different sowings environment of Indian mustard (Brassica junceaL.) in rice based cropping system. *Sci Rep*. **2021**, 11, 5289.
31. Meena, V.S.; Maurya, B.R.; Verma, R.; Meena, R.S.; Jatav, G.K.; Meena, S.K.; Meena, S.K.; Meena, S.K. Soil microbial population and selected enzyme activities as influenced by concentrate manure and in¬organic fertilizer in alluvium soil of Varanasi. *Bioscan* **2013**, 8:3, 931–935.
32. Kumar, S.; Sharma, S.K.; Thakral, S.K.; Bhardwaj, K.K.; Jhariya, M.K.; Meena, R.S.; Jangir, C.K.; Bedwal, S.; Jat, R.D.; Gaber, A.; Atta, A.A. Integrated nutrient management improves the productivity and nutrient use efficiency of Lens culinaris Medik. *Sustain*. **2022**, 14, 3, 1284.

33. Vanlauwe, B.; Diels, J.; Sanginga, N.; Merckx, R. *Integrated Plant Nutrient Management in Sub-Saharan Africa*: From Concept to Practice. CABI: Wallingford, UK, 2002; 352.
34. Chivenge, P.; Vanlauwe, B.; Gentile, R; Six, J. Comparison of organic versus mineral resource effects on short-term aggregate carbon and nitrogen dynamics in a sandy soil versus a fine textured soil. *Agric. Ecosys. Environ*. **2011**, 140, 361–371.
35. Gentile, R.; Vanlauwe, B.; Chivenge, P.; Six, J. Interactive effects from combining fertilizer and organic residue inputs on nitrogen transformations. *Soil Biol. Biochem*. **2008**, 40, 2375–2384.
36. Vonk, W. J.; Hijbeek, R.; Glendining, M. J.; Powlson, D. S.; Bhogal, A.; Merbach, I.; Silva, J. V.; Poffenbarger, H. J.; Dhillon, J.; Sieling, K.; ten Berge; H. F. M. The legacy effect of synthetic N fertiliser. *Eur. J Soil Sci*. **2022**, 73, 3, e13238.
37. Zhang, L.; Chen, J.; Chu, G. Legacy phosphorus in calcareous soil under 33 years of P fertilizer application: Implications for efficient P management in agriculture *Soil use Manag*. **2022**, 38, 3, 1380-1393.