

AGRONOMIC INNOVATIONS FOR THE SUSTAINABILITY OF CROPPING SYSTEMS

Simone ORLANDINI¹, Giulia Galli²

¹ Accademia dei Georgofili, Logge Uffizi Corti, 50122 Florence, Italy
Department of Agriculture, Food, Environment and Forestry (DAGRI), University of Florence, Piazzale delle
Cascine 18, 50144 Florence, Italy

² Fondazione per il Clima e la Sostenibilità, Via Caproni 8, 50145 Florence, Italy

Corresponding author e-mail: simone.orlandini@unifi.it

Abstract

Modern agriculture is confronted with the dual imperative of increasing crop productivity and yield stability to nourish an expanding global population while concurrently mitigating its environmental footprint and adapting to climate change. The transition toward sustainable cropping systems is examined through three synergistic pillars: agroecological practices, digital technologies, and biotechnological innovations. Integrating these domains across the climate-soil-plant continuum establishes a scientifically grounded foundation for sustainable intensification.

Keywords - Agroecology, Precision agriculture, Biotechnology, Climate change, Sustainable intensification

INTRODUCTION

Agricultural production systems worldwide are currently operating at the intersection of unprecedented global demographic pressures and environmental constraints. With global population expanding toward 10.3 billion by the late 21st century and current human resource consumption exceeding the biophysical capacity of 1.7 Earths, agriculture faces a dual challenge: stabilizing and increasing food supplies while systematically reducing ecological degradation. Atmospheric carbon dioxide concentrations have surpassed 420 ppm, accelerating global temperature anomalies and exacerbating the frequency of thermal and hydrologic extremes across agricultural landscapes. Agriculture occupies a distinct position in global environmental dynamics, acting simultaneously as a significant driver of greenhouse gas emissions (representing approximately 18.4% of global emissions when accounting for agriculture, forestry, and land use) and as one of the sectors most vulnerable to climatic disruptions.

To satisfy future human requirements without compromising fundamental ecosystem services, agricultural systems must align with the four core pillars of food security established by the Food and Agriculture Organization (FAO): availability, access, utilization, and stability. Accomplishing this transition necessitates moving beyond incremental adjustments toward a structural transformation of cropping systems. The concept of sustainable intensification provides the overarching framework for this transformation, emphasizing increased productivity and economic returns per unit of land and time while enhancing resource use efficiency and preserving environmental integrity.

To face increasing food demand and growing climate and environmental pressures, systems innovations across three interrelated domains are needed: (1) agroecological innovations and conservation agriculture, (2) digital innovations and precision agriculture, and (3) biotechnological innovations.

DISCUSSION

Table 1. Primary agronomic innovation pillars and their key operational mechanisms.

Innovation Pillar	Core Technologies & Practices	Primary Agronomic Benefits
1. Agroecology & Conservation Agriculture	No-till, cover cropping, crop rotation, carbon farming, IPM	Soil erosion control, carbon sequestration, reduced chemical footprint
2. Precision Agriculture	Sentinel-2 NDVI, VRT fertilization, yield mapping, SWAP/AQUACROP models	Optimized nitrogen dosing, water savings, reduced nutrient leaching
3. Agricultural Biotechnology	New Genomic Techniques (NGTs), microbial inoculants, biopesticides	Abiotic stress tolerance, enhanced natural N-fixation, targeted pest control

1. Agroecological Innovations and Conservation Agriculture

Agroecological strategies serve as the foundational backbone for regenerating soil fertility and establishing ecological resilience. Conservation agriculture relies on co-dependent principles: minimal mechanical soil disturbance (minimum or no-till or direct seeding), permanent organic soil cover using crop residues or cover crops, diversified crop rotations, carbon farming, and agrosilvopastoral integration. Eliminating intensive tillage reduces soil erosion, enhances soil organic carbon sequestration, soil health and microbial activity, and improves soil water retention capacity. Additionally, lower tillage intensity allows the farmer to reduce fuel consumption and work hours. Integrated pest management and circular bioeconomy practices further optimize nutrient cycling and reduce reliance on synthetic chemical inputs.

2. Digital Innovations and Precision Agriculture

Digital technologies enable site-specific management by capturing spatial and temporal variability within individual fields. High-resolution multispectral imagery from Sentinel-2 satellites allows real-time monitoring of crop canopy vigor via vegetation indices such as NDVI. When combined with georeferenced soil sampling, these data generate variable rate application prescription maps for nitrogen fertilization, ensuring optimal nutrient delivery while preventing leaching and volatilization. Combine harvesters equipped with continuous yield-monitoring sensors provide detailed spatial yield maps that complete the precision management loop.

In water-scarce environments, precision irrigation systems leverage crop growth models integrated with numerical weather predictions and satellite imagery. This sequential data assimilation optimizes irrigation scheduling, realizing the objective of 'more crop per drop'.

European agricultural survey data reveal expanding adoption of digital tools, led by digital field records (58% adoption) and satellite-based spatial mapping (22% active adoption, with an additional 10% planning implementation).

3. Biotechnological Innovations

Biotechnology offers critical tools for adapting cropping systems to accelerating climate stress. New Genomic Techniques (NGTs/NPBTs) enable targeted genetic modifications without introducing foreign DNA, accelerating the breeding of crop varieties resistant to drought, salinity, and emerging biological pathogens. In parallel, biological inputs - including beneficial plant growth-promoting rhizobacteria, mycorrhizal fungi, and microbial biopesticides - enhance soil nutrient bioavailability and biological disease suppression, significantly reducing reliance on synthetic agrochemicals.

CONCLUSIONS

1. Conservation agriculture can significantly reduce greenhouse gas emissions from agricultural soils. This mitigation is driven by two key mechanisms: reduced carbon degradation due to minimal soil disturbance (reduced or no-till practices) and a steady increase in soil organic matter - and consequently soil organic carbon - facilitated by mulching and cover cropping. Furthermore, lower operational frequency of agricultural machinery, combined with reduced applications of synthetic fertilizers and pesticides, further shrinks the overall carbon footprint of farming operations. Quantifying these carbon dynamics, a study conducted in Germany estimated that converting from conventional to conservation agriculture can store approximately 500 kg CO₂eq ha⁻¹ in the first year, rising up to 1,350 kg CO₂eq ha⁻¹ annually when the system is maintained in subsequent years. In addition to carbon sequestration, conservation agriculture offers significant broader ecological benefits: for example, it can reduce soil erosion by up to 98%. Given that annual net emissions are estimated at 0.3 t CO₂eq per ton of eroded soil, erosion control provides a substantial secondary benefit for climate mitigation. Moreover, by preventing soil erosion, conservation agriculture preserves essential elements in soil, preventing the farmers from continuously applying synthetic fertilizers to replace lost nutrients. Finally, conservation agriculture enhances soil structure and water infiltration capacity, fosters both above- and below-ground biodiversity, and protects aquatic ecosystems by preventing nutrient-laden runoff and water pollution.
2. Precision agriculture relies on multi-source data acquisition, integrating inputs from soil and machine-mounted sensors, unmanned aerial vehicles or drones, and satellites. Among its most impactful applications is optimized crop fertilization, driven by either proximal machine sensing or remote sensing frameworks. A prime example is variable rate technology for fertilizer application. In a study conducted in central Italy, variable-rate nitrogen fertilization guided by the Nitrogen Nutrition Index (NNI), derived from Sentinel-2 L2A spectral imagery, achieved significant nitrogen fertilizer savings without compromising grain yield or crop quality. Additionally, this satellite-based variable rate technology approach proved highly cost-effective, delivering lower social costs and superior financial rates of return compared to conventional uniform fertilization practices. Beyond nutrient management, satellite technology is widely adopted for GNSS/GPS-assisted guidance and auto-steering systems in farm machinery. These technologies improve labor efficiency while providing reductions of approximately 6% in field operational time and fuel efficiency, lowering fuel consumption by about 6%, further reducing farming carbon footprints and operational costs.
3. Environmentally, biotechnological solutions can minimize toxic chemical accumulation, safeguard soil biodiversity, and mitigate greenhouse gas emissions. Economically and socially, they bolster farmer livelihoods, enhance crop yields, and lower public health risks and environmental remediation expenditures. The adoption of biostimulants and biopesticides significantly curtails farm reliance on synthetic fertilizers and pesticides, preventing harmful residue accumulation in agricultural soils and aquatic sediments. Concurrently, microbial inoculants reduce soil nitrous oxide emissions by substituting or reducing synthetic nitrogen requirements. Additionally, in the case of transitioning biopesticide manufacturing processes to 100% renewable electricity, the climate change impact of production can be reduced by nearly 40%. A comparative LCA study evaluating biopesticides against synthetic chemicals for managing *Xylella fastidiosa* in olive orchards demonstrated that biopesticides exhibited single-score environmental impacts 2 to 861 times lower and freshwater ecotoxicity levels 6 to 8,019 times lower than conventional chemical benchmarks, such as copper oxychloride and deltamethrin.
4. In conclusion, although the aforementioned innovations represent a proven path toward sustainability, agriculture's multifaceted nature prevents one-size-fits-all solutions. The impact of individual techniques will inherently differ depending on factors such as the local climate, farm size, baseline conditions and many more. Instead, maximum efficacy is achieved through systemic integration of the available innovations across the 'Climate-Soil-Plant' continuum. It requires moving

beyond isolated techniques or simple sets of practices, grounding the strategy in evidence-based models and holistic approaches. Rather than relying on fragmented initiatives, success depends on sustaining continuous research, knowledge acquisition, professional training, and clear communication, while simultaneously drawing upon a wide diversity of expertise and skills. Furthermore, building active synergies among all segments and stakeholders in the sector is essential, as is overcoming traditional ideological divisions to adopt innovative, forward-looking approaches. Ultimately, integrating these elements allows the sector to transition toward a cohesive, scientifically backed framework.

REFERENCES

1. Ashraf, M. F., Hou, D., Hussain, Q., Imran, M., Pei, J., Ali, M., Shehzad, A., Anwar, M., Noman, A., Waseem, M., & Lin, X. (2022). Entailing the Next-Generation Sequencing and Metabolome for Sustainable Agriculture by Improving Plant Tolerance. *International Journal of Molecular Sciences*, 23(2), 651. <https://doi.org/10.3390/ijms23020651>
2. Cassman, K. G., & Grassini, P. (2020). A global perspective on sustainable intensification research. *Nature Sustainability*, 3(4), 262-268.
3. C3S/ECMWF (2026). Trend in annual surface air temperature for 1996–2025. Data source: ERA5. <https://climate.copernicus.eu/climate-indicators/temperature>
4. Díaz-Rodríguez, A. M., Parra Cota, F. I., Cira Chávez, L. A., García Ortega, L. F., Estrada Alvarado, M. I., Santoyo, G., & de los Santos-Villalobos, S. (2025). Microbial Inoculants in Sustainable Agriculture: Advancements, Challenges, and Future Directions. *Plants*, 14(2), 191. <https://doi.org/10.3390/plants14020191>
5. Fabbri, C., Delgado, A., Guerrini, L., Napoli, M. (2025). Precision nitrogen fertilization strategies for durum wheat: a sustainability evaluation of NNI and NDVI map-based approaches. *European Journal of Agronomy*, 164, 127502. <https://doi.org/10.1016/j.eja.2024.127502>
6. FAO (2021). Sustainable food and agriculture: Principles and systemic approaches. Food and Agriculture Organization of the United Nations, Rome, Italy.
7. Fenibo, E. O., Ijoma, G. N., Nurmahomed, W., & Matambo, T. (2022). The Potential and Green Chemistry Attributes of Biopesticides for Sustainable Agriculture. *Sustainability*, 14(21), 14417. <https://doi.org/10.3390/su142114417>
8. Freitag, M., Friedrich, T., & Kassam, A. (2024). The carbon footprint of Conservation Agriculture. *International Journal of Agricultural Sustainability*, 22(1). <https://doi.org/10.1080/14735903.2024.2331949>
9. Global Footprint Network (2024). Earth Overshoot Day 2024 approaching. <https://footprintnetwork.org/2024/07/21/earth-overshoot-day-2024/>
10. Hannah Ritchie (2020). Sector by sector: where do global greenhouse gas emissions come from? Published online at OurWorldinData.org. <https://archive.ourworldindata.org/20251125-173858/ghg-emissions-by-sector.html>.
11. Pisante, M., Stagnari, F., & Grant, C. A. (2012). Agricultural Innovations for Sustainable Crop Production Intensification. *Italian Journal of Agronomy*, 7(4), e40. <https://doi.org/10.4081/ija.2012.e40>
12. Pisante, M. (2026). Innovazioni agronomiche nei sistemi colturali erbacei. *Georgofili Info*, 21 January 2026.
13. NOAA Global Monitoring Laboratory (2026). Trends in Atmospheric Carbon Dioxide (CO₂), Monthly Average Mauna Loa CO₂. <https://gml.noaa.gov/ccgg/trends/>
14. Ruder, S.L., Faxon, H.O., Orzel, E.C., Devkota, R. & Bronson, K. (2026). Reviewing the evidence on precision agriculture and environmental sustainability. *npj Sustain. Agric.* 4, 9. <https://doi.org/10.1038/s44264-026-00128-x>
15. Tyczewska, A., Twardowski, T., & Woźniak-Gientka, E. (2023). Agricultural biotechnology for sustainable food security. *Trends in Biotechnology*, 41(3), 331-341. <https://doi.org/10.1016/j.tibtech.2022.12.008>
16. United Nations, DESA, Population Division (2024). World Population Prospects 2024. <http://population.un.org/wpp/>
17. Vázquez Torres, E., Tur Cardona, J., Castro Malet, J., Ciaian, P., Antonioli, F., Fellmann, T. (2025). The state of digitalisation in EU agriculture - Insights from farm surveys. European Commission, Joint Research Centre (JRC) [Dataset] PID: <http://data.europa.eu/89h/27a677f1-6b79-4088-a26c-996b1af8d990>