https://doi.org/10.1038/s41467-025-64450-7

Advancing sustainable agricultural transformation through the synergy of automated experimental platforms and living labs

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Transforming agricultural landscapes to be more sustainable and resilient requires integrated and multidisciplinary approaches. Linking automated experimental platforms with living labs can accelerate knowledge gain, enhance interdisciplinary collaboration, and support real-world change by addressing key challenges in current agricultural systems.

Agriculture today faces pressing challenges, including food security, biodiversity loss, degradation of natural resources, environmental pollution, and both the impacts of and risks posed by climate change[1]. A key obstacle in addressing these challenges is the inefficient transfer of scientific knowledge into practice. Despite advances in research, few results translate into practical agricultural improvements[2]. This widening gap between research and innovation hinders progress toward sustainable and resilient agricultural systems. Without more effective integration and application of scientific insights, the transition to sustainable agriculture would remain fragmented.

To overcome this challenge, we highlight an approach with two interconnected pillars: pillar 1) consistent development of a holistic, automated experimental platform and pillar 2) their integration into co-design approaches for agricultural transformation. We argue that by linking experimental platforms with living labs, we can establish an effective, multi-directional exchange of knowledge—ensuring that scientific advancements are rapidly tested, refined, and implemented in agricultural landscapes.

Developing holistic, automated, versatile experimental platforms for agricultural research

Addressing agriculture's complex challenges and overcoming research limitations caused by fragmentation, a system-based approach is increasingly advocated[3]. This, however, requires comprehensive knowledge to identify key processes that are relevant for understanding, developing and managing sustainable and resilient agricultural systems.

Traditional assessments often evaluate aspects separately, such as soil nutrient and water dynamics, greenhouse gas (GHG) emissions and crop growth and yields. However, understanding land management and climate change responses necessitates evaluating feedback more comprehensively across different spatio-temporal scales, integrating natural and agricultural sciences as well as socio-economics. We propose that holistic, automated experimental platforms can serve as multidisciplinary hubs that integrate process-based knowledge over a wide range of scales. Here, we define an experimental platform as a framework of integrated devices and software components (experimentation, data analytics, and modeling) that enables holistic, system-based collection and understanding of agroecosystems. It includes various measurement tools to capture climatic, ecological, (eco-)physiological, biochemical and hydrological parameters, alongside software to store, remotely access, analyze, and visualize data automatically.

Unlike traditional long-term experiments, experimental platforms are modular, flexible and can be adapted to specific research needs. Currently, emerging platforms automatically quantify field-scale GHG and/or ET flux dynamics as well as automate phenotyping[4,5], crucially linking physiological measurements to yield. The great potential of experimental platforms lies in their ability to integrate expertise in crop science, biodiversity, biogeochemistry including the partitioning and resource use efficiency parameters (e.g., for water, nitrogen and carbon). Moreover, they have significant potential to advance hierarchical understanding across scales (e.g., from phyllos- or rhizosphere to agroecosystems and landscapes) and provide integrated information on processes and fluxes for comprehensive crops, agroecosystem and landscape modelling. Analyzing system feedback rather than isolated processes, promises the integration needed to understand and predict system dynamics. Hence, these platforms can facilitate the development of more effective management strategies.

One example of such a platform is "AgroFlux" (Fig. 1). In its current form "AgroFlux" consists of multiple observational techniques to address processes at different scales ranging from the leaf to the agroecosystem and landscape scale and from minutes to months to seasons. This necessitates the development and integration of both high-cost and low-cost infrastructure elements (e.g. for validation purposes or spatial representation[6]). A fully automated gantry crane system ("FluxCrane", Fig. 1a)[7,8] detects isotope-enabled water and matter flux dynamics, crop phenology, and stress indicators, enabling high-resolution, multi-treatment spatial and temporal assessments. Flexible and adaptive in-situ stable isotope monitoring networks ("IsoFlux", Fig. 1d) facilitate net flux partitioning and tracing of process feedbacks and signals through the soil-plant-atmosphere continuum. Equally versatile and particularly low-cost measurement infrastructure ("SensorWeb", Fig. 1c) combined with (drone based, Fig. 1b) remote

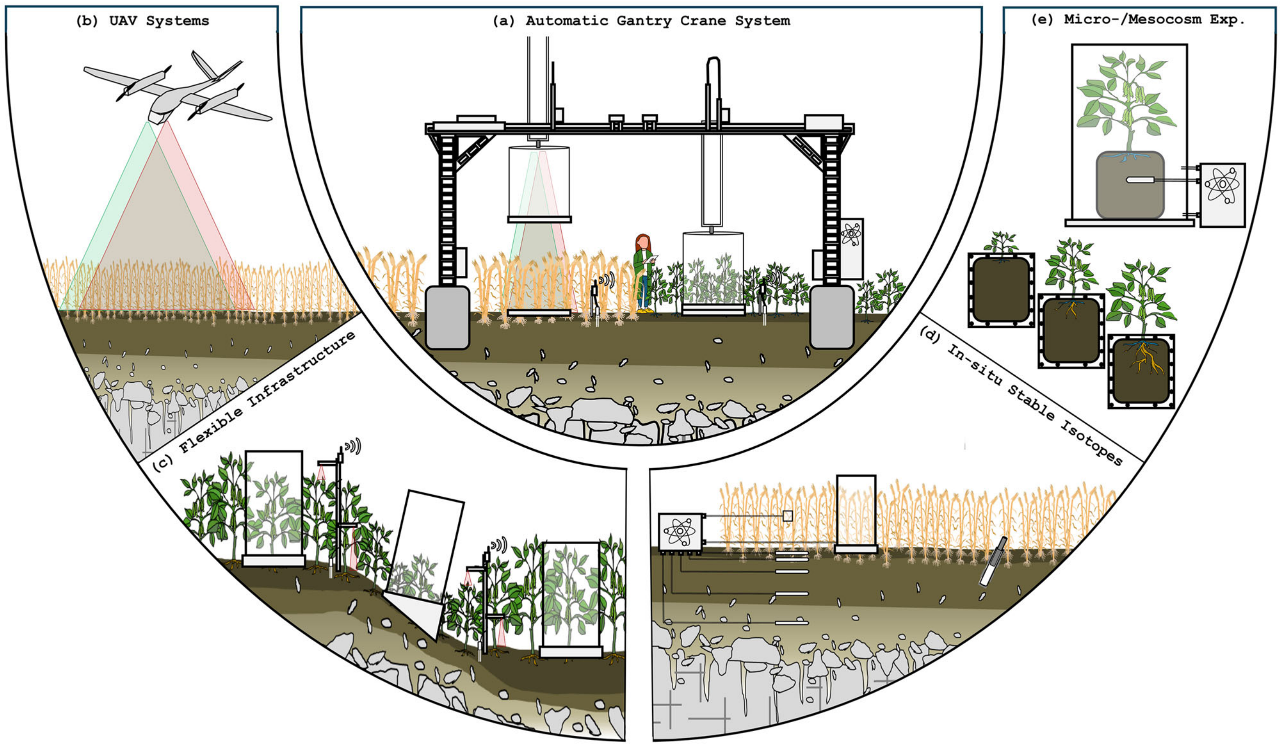

Fig. 1 | Idealized current stage of the "AgroFlux" experimental platform (natural science perspective). The platform features: an **a** automatized gantry crane robotic system to detect crop growth and phenology (e.g., proximal sensing of spectral plant indices such as normalized difference vegetation index (NDVI) or ratio vegetation index (RVI) as well as infrared (IR) canopy temperatures), greenhouse gas (GHG) and evapotranspiration (ET) flux dynamics (flow-through non-steady-state closed canopy chambers); an **b** unmanned aerial vehicle (UAV) based remote sensing for upscaling purposes (satellite-based remote sensing is not yet integrated, due to current limitations regarding temporal resolution and cloud cover making drone-based sensing more suitable for capturing short-term and small-scale variability, however, as spatial and temporal resolution improves, satellite-based remote sensing will likely become a key component for future integration and regional upscaling); **a**, **c** flexible, adaptive measurement infrastructure (e.g., internet of things (IoT) sensor network, canopy chambers, proximal sensors for NDVI, RVI; IR canopy temperatures); an **d** in-situ stable isotope (carbon, nitrogen and water) monitoring along soil-plant atmosphere gradients (flux separation); as well as **e** experiment based determination of processes within soil-plant atmosphere interphase (e.g., plant-soil feedbacks).

sensing allows for spatial integration and upscaling to the landscape scale as well as utilization of a sensor platform in remote regions. Here, we can particularly learn from developments in smart and precision agriculture: i.e. using state-of-the-art plot-based sensing to calibrate and develop cost-efficient data collection approaches and upscaling[6].

A modelling component is crucial for a holistic experimental platform but is presently not developed. We propose that experimentation and modelling need to be developed in synchrony to enhance feedback between them. For example, high-resolution data on how plants respond to stress—like how roots take up water during drought or how heat affects crop growth and yield[9]—or on how interactions in the root zone influence nutrient, carbon, and water cycles[10], can greatly improve process-based models and make their predictions more accurate. At the same time, model-driven approaches can support efficient selection of observation variables. For instance, process-based crop models combined with advanced sensing tools can predict plant ideotypes[11] to improve crop productivity and food security under varying environmental conditions, including climate change[12]. Finally, despite the importance of automation in experimentation and data analysis, many research questions or scientific disciplines crucial for a holistic experimental platform are constrained by destructive, manual sampling (e.g. microbiology, root and partly soil sciences) or the need for environmental manipulation. It is crucial to consider this when designing experimental platforms to avoid exclusion and fragmentation of scientific disciplines (Fig. 1e).

Integrating agricultural research platforms into living lab structures

Transforming agriculture sustainably requires both scientific understanding of agroecosystems and active stakeholder engagement in adapting innovations – a multi-directional approach that integrates research with transformative practice, but remains underdeveloped[4]. Central to this are co-design approaches, which consider relevant actors, including researchers, for the joint development of innovations to support agricultural transformation. Living labs have emerged as a promising framework for fostering such co-design innovations. While definitions of living labs vary, we here briefly refer to living labs as "both an approach and an arena for supporting experimentation in real-life settings with a wide range of actors"[13]. Living labs function as hubs for research, development and innovation focusing on transformation towards sustainable agriculture. An important step is to develop governance structures (e.g., steering committees) and actor

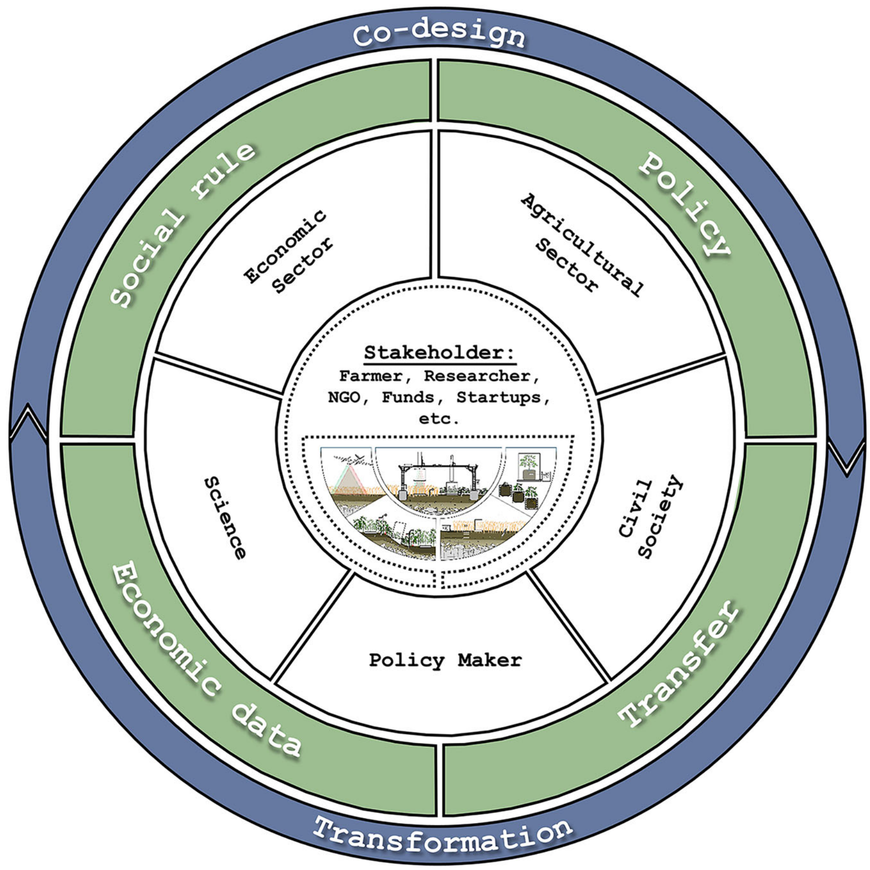

Fig. 2 | Role of an experimental platform as a versatile, modular infrastructure that serves as the core of a living lab. In this setting, relevant actors from different sectors—including farmers, researchers—collaborate to co-design future agricultural developments and drive the transition toward sustainable practices. This integration has two key aspects: 1.) It enables a holistic, system-based understanding of the effects of land-use or management changes, helping to identify and promote "best practices" and support their transfer to real-world settings; 2.) By merging experimental platforms with living labs into unified, transfer-oriented research hubs, barriers to knowledge transfer are reduced. Working together in the same hub ensures that all actors share a common focus and that scientists can efficiently address current agricultural challenges.

networks that include researchers, farmers, policy makers, industry representatives, and civil society. This includes collaboration and strategic partnerships with universities, research institutions, industry, and farmer organizations[3].

We propose integrating automated experimental platforms into multi-directional and co-design approaches as a key strategy to enhance the scalability and relevance of living lab activities. This integration ensures that scientific discoveries are effectively applied in real-world settings, while insights and challenges from practice help refine research priorities at broader scales (Fig. 2). Experimental platforms generate high-quality data under controlled yet realistic conditions, offering insights into cause-effect relationships and technical performance. Living labs, on the other hand, engage farmers, advisors, and other stakeholders in participatory processes that capture socio-cultural, economic, and agroecological diversity. Their combination allows for iterative co-design and testing of innovations across diverse contexts.

To support this synergy, flexibility and modularity of experimental platforms (pillar I) are essential. Living labs typically operate through localized use cases, where innovations are tested and validated under specific conditions. However, upscaling remains a key challenge due to variability across regions, actors, and farm systems. Flexible, modular platforms can be adapted, scaled, or reconfigured to meet evolving research and practice needs. Automation enables scaling but can risk exclusion or oversimplification; living labs mitigate this by ensuring inclusive, context-sensitive development. Together, these systems enable both scaling out (reaching more users) and scaling deep (embedding change in practices and values), thereby strengthening the impact, adaptability, and societal relevance of research infrastructures.

The development of a co-design approach that is consistently inclusive of the full spectrum of natural, agricultural and social sciences as well as other actors is key in achieving this goal[2]. This also requires synergizing the analysis of data from different disciplines. To support this, data infrastructures and data management plans need to be developed that can handle different types of data with a wide range of variables and perspectives, emphasizing the potential interconnectedness of data across disciplines. This requires collaborative data collection and analysis schemes. We believe that an important catalyst for collaborative research is the development of automated data observation and exchange across disciplines. For experimental sciences, this includes a critical step from automated measurements (current state) to automated data analysis and data driven modelling to determine budgets, partitioning fluxes and harvest related parameters. A closer link between experimental and modelling approaches, beyond the current state, could facilitate a better knowledge of key processes and observation parameters, which would benefit use-case specific experimental platforms and the link between researchers and other actors of living labs. Thus, the experimental platform could be applied to develop standardized, machine-readable data for land managers' GPS-linked tractors and smartphones[11]. Also, social dimensions should not be treated merely as background context in experimental platforms, but rather as active components in their design and analysis. Integrating social rules, policies, and economic data is essential to ensure that outcomes are not only scientifically robust but also relevant and applicable to real-world policy and practice. One practical example is the testing of result-based payments for ecosystem services within agricultural experimental platforms embedded in living labs, where incentive structures are co-designed with stakeholders and supported by robust monitoring systems to link payments directly to measurable environmental outcomes[14]. When fully developed, this will not only advance knowledge but also support actors with science based, quantified target responses to management actions from e.g., low-cost measuring devices linked to mobile apps. Moreover, also farmers themselves will benefit from automation (e.g., data driven precision agriculture, robotics) by increasing efficiency, reducing labor costs, optimizing resource use, and improving crop yields and quality.

Outlook

Despite their potential, current sensor platforms like "AgroFlux" lack both a holistic natural and agricultural science perspective and the capacity to effectively transfer new knowledge into practice. The integration of interdisciplinary experimental platforms with living labs creates a vital interface that accelerates the transformation toward sustainable agriculture by enabling iterative feedback, co-design, and faster adoption of tested innovations.

In order to fully develop pillar I of our approach, experimental platforms need to be developed covering key elements from all relevant scientific disciplines and transformed into versatile modular infrastructures that can be tailored to specific challenges and innovation cases in real-world settings. Major development needs are increased flexibility and modularity of the included experimental measurement techniques and increased automation in terms of not only data observation but also especially data analysis. To enhance flexibility, new generations of field robots can enhance automation of many observation variables. Moreover, an efficient link between experiment, data management and analytics and modelling approaches needs to be established to enhance the identification and understanding of the dynamics of emerging properties of agricultural landscapes. One example for this is the development of digital twin approaches[15].

Emerging properties of agroecosystem are shaped not only by biological, chemical or physical processes but rather determined by the complex interactions within the social-ecological system. They extend beyond our present understanding of agroecosystems and agricultural landscapes dynamics and require the integration of experimental platforms with living labs (pillar II). Major steps in this integration include aligning living labs with the needs of local actors, embedding experimental platforms to test solutions in real-world settings, identifying scalable innovations for living labs networks, and generating scientific insights to fit different scales and contexts.

However, despite the promising contributions of automated experimental platforms and living labs, they also pose significant socio-political challenges, particularly related to equity and data governance. As with previous technological revolutions, these innovations are often tailored to a narrow range of commodity crops within conventional, large-scale farming systems, leaving small-scale, diversified, and agroecological farms underserved[16]. This trend risks reinforcing existing inequalities in access to resources, technological capacity, and influence. Moreover, concerns around data ownership, privacy, and control remain unresolved, especially for farmers with limited institutional support. To ensure inclusive innovation, it is essential to actively engage marginalized groups and harder-to-reach stakeholders who may lack the visibility or capacity to advocate for their needs in the digital transition[17].

Successful integration of experimental platforms with co-design requires long-term commitment. Governments and institutions should provide sustained funding, grants, and recognition to support collaborative networks, enabling scalable and lasting solutions. Investment in long-term experimental platforms is essential for success.

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Received: 6 May 2024; Accepted: 17 September 2025;
Published online: 25 September 2025

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Acknowledgements
The authors acknowledge John Marshall for proof reading and checking grammar, punctuation, and spelling errors. MH acknowledges funding from the COINS project (ID: FKZ 01LL2204B), financed by the German Federal Ministry of Research, Technology and Space. MD acknowledges funding by the Leibniz foundation SAW project ISO-SCALE (ID: K444/2022) and fruitful discussions in the Leibniz Network Earth and Society. CC acknowledges funding from the Digital Agriculture Knowledge and Information System (DAKIS) Project DAKIS Project (ID: FKZ 031B0729A), financed by the German Federal Ministry of Research, Technology and Space.

Author contributions
M.D,. M.H., C.C. and J.A. conceived the initial idea and jointly wrote the manuscript. M.H., M.D., C.C., J.A., F.E., K.B.-B., M.H., R.K. provided valuable comments for improvement, contributed to writing and agreed on the final version of the manuscript.

Competing interests
The authors declare no competing interests.

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Peer review information *Nature Communications* thanks Maaz Gardezi and the other anonymous, reviewer(s) for their contribution to the peer review of this work".