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Digital Regenerative Agriculture

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Intergovernmental organisations are pushing for ecological renewal with ever-increasing urgency. The trinity of Precision, Digital, and Smart (Ag 4.0) Agriculture encapsulate the tools best positioned to quantify the contributions farmscapes make towards these ends. However, work under these banners to date has rested on productivity and efficiency. Limiting negative environmental outcomes, when acknowledged as an objective, is most often presented as possible through ex-post evaluations. Conversely, Regenerative Agriculture champions environmental renewal as the pathway to more resilient and consistent production systems but currently lacks scientific validation. A synergy of the two will enhance both by (i) developing data on environmentally forward systems, (ii) presenting new challenges for monitoring, and (iii) by laying a foundation for the farmer-led data-driven site-specific refinement of management systems that prioritise outcomes for production through enhanced environmental function. All of which, when passed through a digital supply chain, will contribute substantially to product provenance and, in turn, consumer confidence.

What is Regenerative Agriculture?

While having earlier origins[1,2], over the last decade Regenerative Agriculture has come to occupy a considerable position on the global agricultural stage[3,4]. Though this rapid increase in interest has not occurred without conflict between its primarily grassroots supporter base, more conventional farmers, and established agricultural science[5,6]. While disagreements focus on the applicability of practice, scalability, and the impact associated yield reductions could have on feeding the growing human population[3,6], the idea of regenerated agricultural landscapes, without a formal definition[4] or centralised supporting body, has captured global interest within and outside agriculture[7]. The collection of farmer leaders, non-farming/farming supporters, and the systems they manage are now best viewed as an agricultural movement[8].

As a movement, Regenerative Agriculture seeks to address crises of soil health, biodiversity, and food security[3]. Concerns are shared by intergovernmental organisations and reflected in several of the United Nations Sustainable Development Goals. Despite initial trepidations academics have begun to engage with and even sought to clarify the movement's direction[4]. Formal definitions were put forward, in 2020 by Schreefel et al.[9].

> *An approach to farming that uses soil conservation as the entry point to regenerate and contribute to multiple provisioning, regulating, and supporting ecosystem services, with the objective that this will enhance not only the environmental, but also the social and economic dimensions of sustainable food production.*

And in 2022 by O'Donoghue et al.[8].

> *Any system of crop and/or livestock production that, through natural complexity and with respect to its inherent capacity, increases the quality of the product and the availability of the resources agriculture depends upon, soil, water, biota, renewable energy, and human endeavour.*

These definitions present regenerative systems as those that rebuild depleted natural resources and enhance ecosystem service delivery by reinstating natural cycles. This intention echoes those of the movement's early proponents[1,2] and its current farmer leaders[10–12]. As the above definitions were drawn from existing literature, it follows that others have come to similar conclusions[5].

To support and connect interested producers and consumers, two leading regenerative agriculture organisations have established performance (Savory Institute) and practice (Regenerative Organic Alliance) based certification programmes[13,14]. While both acknowledge that practice suitability will vary with soil type, climate, regional biota, socioeconomic, and political factors; established agricultural science offers potentially more rigorous methods of identifying differences in the capacity and changing condition of those systems. Quantifying both will dispel disagreements, guide practice adoption, and tend toward better outcomes for the environment, product quality, and the confidence of both farmers and consumers.

What is Digital Agriculture?

The terms Precision Agriculture, Digital Agriculture, and the more recent Smart Agriculture or Agriculture 4.0 are sometimes conflated in the

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literature[15,16] or presented as sequential technologically enabled evolutions of one another[17,18]. Like Regenerative Agriculture, Precision Agriculture also originated in the 1980's but followed a very different uptake trajectory. Initially, Precision Agriculture was implemented through soil mapping, variable rate technology (VRT), and vehicle guidance through global navigation satellite systems (GNSS). Uptake across Northern America, Europe, Brazil, Japan, and Australia was considerable but piecemeal[19]. Shortly after the turn of the millennium, the introduction of wireless sensor networks (WSN) through the internet of things (IoT) enabled real-time monitoring of certain farm attributes. This saw some promote the transition from precision to "decision" agriculture[20] through a new Digital Agriculture. However, with the proposal of Industry 4.0 by the German government[18] and the vision of increasingly informative analysis through ever larger data streams, Smart Agriculture or Agriculture 4.0 is being positioned to eclipse its predecessors. Currently, all terms persist, along with Climate-Smart Agriculture and "farming" suffixed variations of each[15].

Early definitions that captured the scope of Precision Agriculture proved elusive[21]. As a result, for some, it was reduced to the practices mentioned above and the narrative of evolution was established, see Fig. 1. However, prior to the perpetuation of the subsequent (potentially auxiliary) terms, the broad goal of Precision Agriculture was to increase the number of correct decisions per area and over time[21]. Within this vision, the introduction of wireless sensor networks (WSN), the internet of things (IoT), big data, and robotics were predicted to contribute to this goal by enabling regular environmental auditing and triggering or carrying out management activities[21]. At the same time, these regular measures of environmental condition, partnered with similarly attained measures of product quality, were envisaged being passed to consumers through a digitally enabled supply chain—contributing substantially to product provenance[21]. This vision has persevered through Digital Agriculture and Agriculture 4.0[22,23]. Though currently, environmental monitoring, in this space, is typically poised to minimise or limit negative impacts from agriculture[16,22] rather than to support or synergise through one another. Figure 2 places practices associated with each phase of the evolution narrative into the broader context of applying digital technologies to agricultural spatial and temporal decision making.

While digital technologies have opened new avenues of communication, ensuring fit-for-purpose information reaches farm decision makers requires further work. This is the prescribed domain of Agriculture 4.0[15]. Despite the ongoing nature of this process, Agriculture 5.0, heralded by the introduction of automatisation via autonomous aerial and ground-based vehicles (AV), is already materialising[17]. Will each technological step or leap require a new agricultural iteration? Taking an unindoctrinated perspective, that of consumers, funders, or even farmers—the intended end users and benefactors of these "agricultures"—unnecessary technical complications can lead to disengagement as has been seen with greenwashing in Organic Agriculture[24] and donor fatigue surrounding Sustainable Agriculture Alternatives in the 1990's[25]. To stem complication, Digital Agriculture will here refer to the application of digital technology in crop and livestock systems to gather, interpret, and communicate data in order to guide decision making on farms and along the supply chain—or simply *data-driven agriculture*[21].

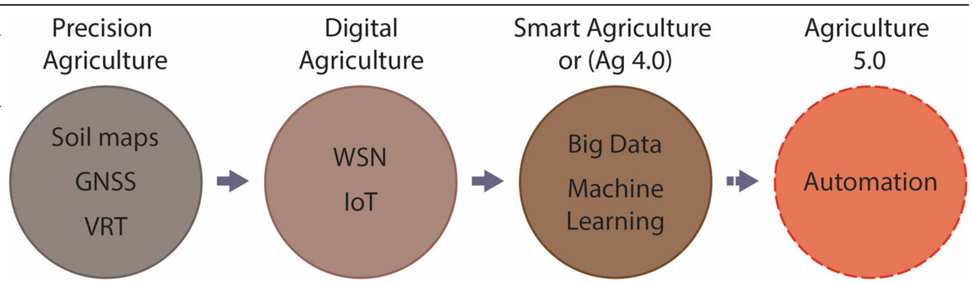
What could a Digital Regenerative Agriculture look like?

A Digital Regenerative Agriculture through quantification, evaluation, and peer-to-peer collaborative innovation will further the goals of both Digital and Regenerative Agriculture. Quantifying the capacity and condition of environmentally forward agricultural systems will not only validate the efforts of individual farmers; it will also allow for the meaningful comparison of agricultural systems and ensure that new adopters take on practices that are appropriate for their systems. The quantified changes in condition and management information will, through a digitally enabled supply chain, present several additional layers of product provenance for consumer evaluation. Thus, the *regenerative* will bring to the *digital* an enhanced environmental direction and, through engaged consumers, an environmental monitoring programme that could become self-sustaining; while the *digital* will validate *regenerative* performance, ensure consumers are empowered, and that new adopters are supported. Challenges to effective quantification, evaluation, and communication exist, though much work towards solutions has already been completed under a variety of agricultural banners.

Precision agriculture introduced the idea of management zones, "farming by soil", a term coined by Roberts in 1993[26]. This concept provides the basis upon which the monitoring of crop, water, belowground biodiversity, energy capture/consumption, and other soil chemical and physical properties can begin. Nesting these traditional management zones within zones scaled relevantly to other farmscape attributes, above-ground biodiversity and human endeavour for example, will allow for the quantification of natural and human capital within elements and across farmscapes. Not just zones in fields but also hedgerows, watercourses, and reserves. The carefully considered comparison of the resulting farmscape elements will provide insight into potential capacity and relative current condition. Work in this vein has been explored for soil[27] and is becoming more accessible through digital methods[28]. Spatial-temporal monitoring and comparison at this resolution, as supported by remote and proximal sensing[29], will strongly support on-farm experimentation and the drive towards site-specific management systems[21]. Practices like integrated pest management will introduce new sensing challenges and pose the need for inter-farmscape-element interactions, for example, between hedgerows/refuges and fields. These evaluations will likely be guided by Landscape Ecology[30] and the science of Agroecology[31]. The integration of these approaches, to enable a Digital Regenerative Agriculture, is visualised in Fig. 3.

Communication between farms, farmers, and the supply chain will be complicated by data volume and security. Methods for data evaluation have been and continue to be explored through Smart Agriculture[32]. These volumes can significantly be reduced by filtering for relevancy to the end user. For a farmer filtering could be based on the capacity and condition of their system, while for a consumer along or at the end of the supply chain, information could be provided at varying layers of detail to satiate respective levels of interest. Security through this process, in terms of resistance to data breaches and ensuring that data owners have control over how and who their data is shared with, will be of the utmost importance[16]. Distributed ledger systems such as blockchain technology appear to be the most viable option at present, it allows for more transparent, reliable, immutable, and decentralised data storage[33]. While such technology was previously the domain of large corporate farming, smaller-scale farmers are beginning to

Fig. 1 | The Precision, Digital, Smart, and eventual Agriculture 5.0 evolution narrative with associated practices. Acronyms: Global Navigation Satellite Systems (GNSS), Variable Rate Technology (VRT), Wireless Sensor Networks (WSN), and Internet of Things (IoT).



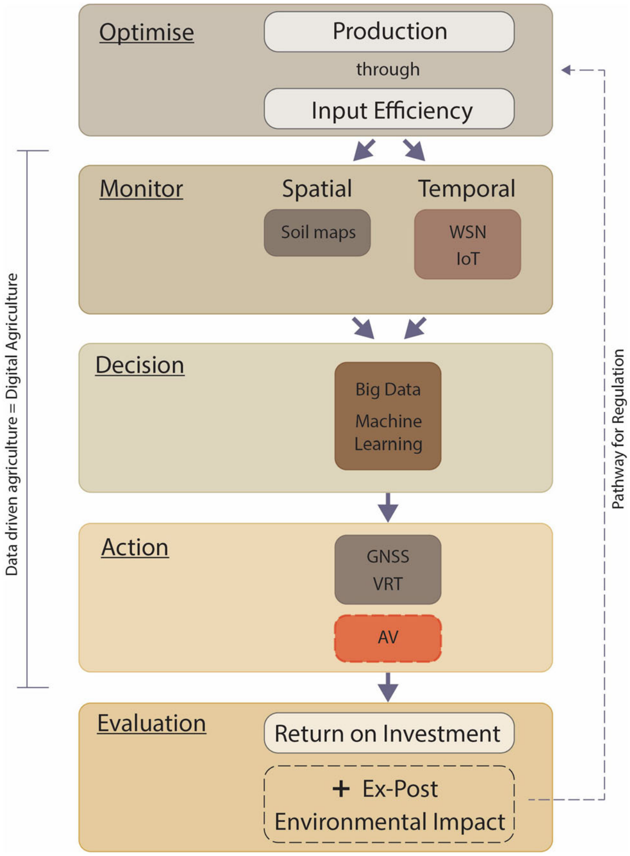


Fig. 2 | Data-driven agriculture—an alternative view of the Precision, Digital, and Smart development narrative. This view sees the introduction of new technologies to farmscapes as having continued to inform decision-making regarding the targets of optimisation production and input efficiency. Acronyms: Wireless Sensor Networks (WSN), Internet of Things (IoT), Global Navigation Satellite Systems (GNSS), Variable Rate Technology (VRT), and Autonomous Vehicles (AV).

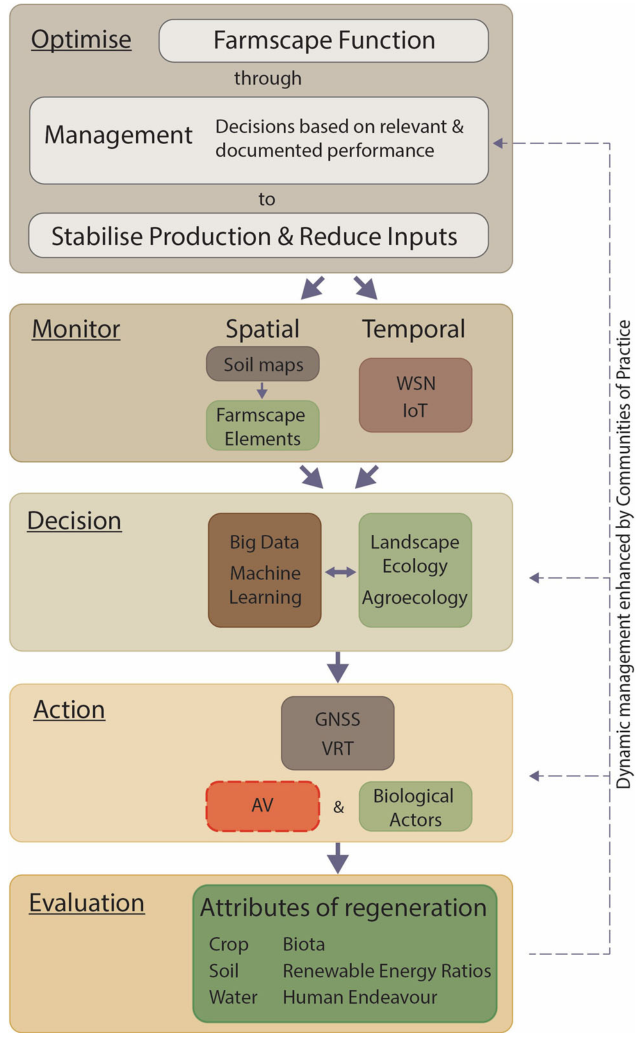


Fig. 3 | Digital and regenerative approaches to agriculture synergised to prioritise ecosystem renewal and production through more informed management decisions. Digital methods offer the means to quantify a farmscape element's inherent capacity and changes in condition, while regeneratively aligned systems of thought, will guide data interpretation, offer another mode of automatisation, and provide wider measures of evaluation. Acronyms: Wireless Sensor Networks (WSN), Internet of Things (IoT), Global Navigation Satellite Systems (GNSS), Variable Rate Technology (VRT), and Autonomous Vehicles (AV).

incorporate similar technologies[22]. A digitally enabled regenerative farmscape and supply chain is pictured below in Fig. 4.

Acquiring the vast quantity of data required to realise a Digital Regenerative Agriculture presents a considerable challenge. In technologically enabled environments, labour and coordination will be the primary issue[16]. In less technologically enabled environments, access to digital methods of measurement presents a more comprehensive barrier to engagement[34]. Agronomists may be the best candidates to resolve the question of on-the-ground labour[35]. Agronomists frequently visit farms, have close knowledge of individual systems, wider knowledge of the region, and considerable scientific training. Some already offer on-farm Precision Agriculture services[36,37]. Increasing the number of system attributes to, or which can be, monitored will further diversify the offerings of this sector. Coordination of monitoring efforts through multiple service providers and inaccurate reporting presents a secondary problem[16]. Quantified performance-based consumer markets provide an incentive, while temporal, spatial, and management-system-capability-based auditing offers a potential solution.

Where access to technology is limited, due to local infrastructure or individual farm capital, products may be excluded from certified markets for being unable to conform with reporting methodologies. Where mobile phone or web-based applications are available[34], but farm capacity and condition have not been confirmed, the specificity of information accessible to farmers will be limited. Conversely, in such systems, which often coincide with less socio-economically advanced regions, price premiums and eco-credits will have the greatest impact. To ease the barrier to engagement, some monitoring equipment could be collectivised. However, a more forward-thinking approach could see support from more socio-economically advanced regions directly justified through homo- or future-clime research[38]. In such a situation careful consideration of investment sources will be needed to ensure local data, knowledge, and business sovereignty is maintained.

This is not the first time technology has been proposed as a means of progressing the ecological renewal of our farmscapes; Organic Agriculture[39], Agroecology[40], Precision Agriculture[21]; nor the amalgamation of movements generally; Organic-Agroecology[39] or Regenerative-Permaculture[41]. These movements have different knowledge pools and intended outcomes, hence their varied uptake. As a movement Regenerative Agriculture focuses on restoring the immediate and wider environment an agricultural system operates within. When defined in terms of performance, it is positioned well as an umbrella term, under which, different approaches to agriculture and specific management practices can be appraised with reference to the systems in which they are applied. Digital Agriculture offers the current best opportunity to validate that performance spatially and temporally while also providing the means to share outcomes appropriately. A synergy of the two presents the opportunity to systematically and with greater confidence, tackle some of the most wide-reaching challenges facing Agriculture and humanity.

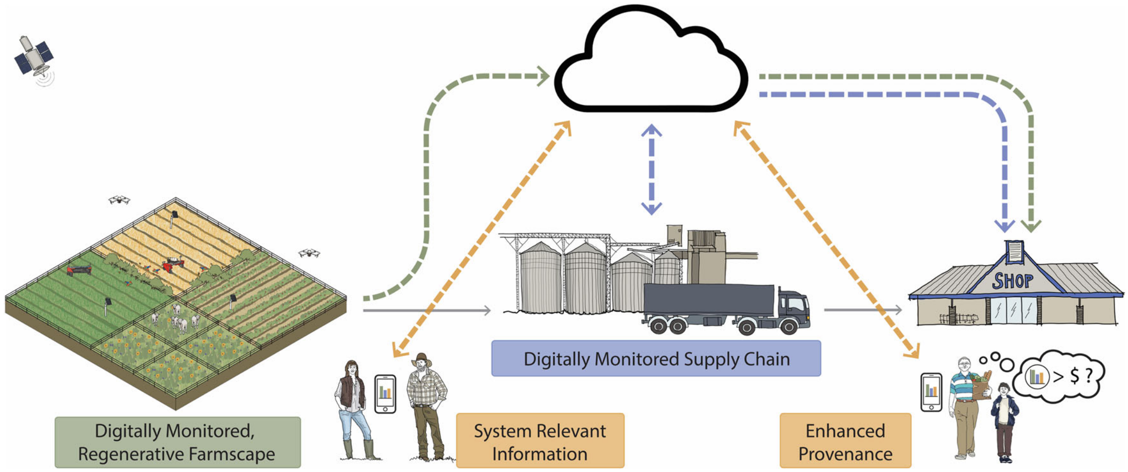


Fig. 4 | A Digitally enabled Regenerative Farmscape and Supply Chain. From left to right, a mixed farming system incorporating several practices associated with Regenerative Agriculture, rotational grazing, cover cropping, nature refuges, and crop rotation. The respective farmscape elements are digitally monitored for changes in condition. Data is passed to the cloud and, at farmer discretion, shared with subsequent stages of the supply chain and farming communities of practice. Communities of practice gain system-relevant information, and the process enables data-backed collaboration. Subsequent stages of the supply chain add their own packets of data to the end-product by similar processes. A data interface makes relevant information available to end consumers and enhances product provenance.

Conclusion

1. Regenerative agriculture focuses on enhancing natural cycles on farms to stabilise production. It has a large public and farming following but currently lacks scientific validation.
2. Digital agriculture has here been defined as data-driven agriculture. In this light, it encompasses practices that some associate exclusively with Precision Agriculture, Smart Agriculture, and Agriculture 5.0. Regardless of terminology, in this domain, environmental impacts have been secondary to evaluations of productivity and efficiency.
3. A Digital Regenerative Agriculture would prioritise farm environmental performance as a driver of productivity and provide the means to effectively quantify system capacity and condition. This, in turn, would streamline currently separate but aligned research efforts, improve farmer-to-farmer collaboration, and through a digitally enabled supply chain, improve consumer assurance, be they purchasing environmental services, surveying natural capital, or buying groceries from a supermarket.

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Competing interests
The authors declare no competing interests.

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