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# Digital agriculture to design sustainable agricultural systems

The global food system must become more sustainable. Digital agriculture — digital and geospatial technologies to monitor, assess and manage soil, climatic and genetic resources — illustrates how to meet this challenge so as to balance the economic, environmental and social dimensions of sustainable food production.

Bruno Basso and John Antle

Fifty years ago, many people doubted the ability of the world to feed itself. While food security remains a challenge for the poorest people, the global food system has been so successful in producing cheap food calories that today three-times more people in the world are obese than underweight due to malnutrition[1]. The current food system is able to do this largely because of crop and livestock production technologies that produce and deliver more food calories to more people than was previously thought possible. But agriculture's contributions to greenhouse gas emissions, water pollution and biodiversity loss show that major agricultural systems are on largely unsustainable trajectories[2]. As Schramski et al.[3] point out, changing the way we produce and use energy in agriculture as well as the rest of the economy must be an important part of meeting the sustainability challenge. However, it seems unlikely that a development pathway for a human population approaching 10 billion could be achieved with less total energy use. And since some environmental costs will be associated with increased energy use and a substantially larger human population, achieving a more sustainable development pathway will involve managing trade-offs in complex natural and human systems among economic, environmental and social dimensions of human well-being[4]. It now appears likely that moving agriculture towards a more sustainable development pathway will depend largely on crop agriculture, particularly if the sustainable human diet is to be largely based on plant-based foods. This will involve trade-offs associated with the demands such a pathway will place on land, water and genetic resources in many parts of the world[5].

The best hope for meeting the challenge of sustainable agricultural development lies in the ongoing process of innovation now taking place using modern genetic and information technologies to increase agricultural productivity while balancing economic, environmental and social outcomes associated with agriculture and the food system. Genetic improvement is a necessary but not sufficient part of this strategy, as we learned in the Green Revolution of the twentieth century, because environmental outcomes depend on how crop production is managed at the field scale as well as its interactions with ecosystems across the landscape. Much attention has been paid to the key role that data acquisition plays in improving crop management — but improvements in system performance will come about only when agricultural science can make effective use of these 'big data'. Improved data and analytics will need to be incorporated with agronomic science, that is, what we call digital agriculture (DA) — a set of digital and geospatial information technologies that integrates sensors, analytics and automation to monitor, assess and manage soil, climatic and genetic resources at field and landscape scales.

So-called precision agriculture (PA)[6] began to be implemented in the early 1990s ostensibly to increase profitability and reduce the environmental impact of crop-based systems by applying variable inputs according to spatial variability of crop growth[7]. However, there is little evidence as yet demonstrating widespread economic and environmental benefits of precision management technology[8]. Like many mechanical technologies, the economic benefits appear to be greatest for larger farms that can spread their fixed costs over many acres, and that can reduce labour costs through automation. Thus, profitability and adoption in the United States is highest among larger farms, with profitability only slightly higher on average among adopters, and input use only marginally lower on average, consistent with the finding of minimal environmental benefits from PA as currently implemented[8]. One explanation for the failure to achieve more substantial and widespread improvements in environmental performance is the lack of effective policies to incentivize the implementation of technologies such as PA in ways that achieve their promise of environmental improvement. For example, in the US Midwest, both surface and groundwater quality continue to be severely impacted by high levels of agricultural chemical use and pollution caused by surface runoff and leaching to groundwater, despite a variety of policies implemented since the 1980s to reduce soil erosion and runoff[9].

A related explanation for the failure of DA to deliver on its promises is that, thus far, algorithm developers for precision management have lacked the data and computational tools needed to convert complex geospatial information on soil and plant status into appropriate crop management actions. Misinterpretation and misuse of data appears to be a consequence. For example, many farmers utilize precision technology to apply more nitrogen (N) fertilizer to low-yielding portions of rain-fed fields in the hope of increasing yields, rather than less N to avoid fertilizer losses through leaching and runoff of N that crops cannot use. This tendency is compounded by apparent conflicts between farmers' goal to maximize economic returns, and the objective of input suppliers to maximize sales of inputs. Thus, ironically, precision management tools may result in lower economic and environmental sustainability if not used appropriately.

Recent research suggests that improvements in DA technology could transform these trade-offs into the win–win synergies that were envisioned for PA, and also help re-design agricultural landscapes for sustainability[10]. Given the inherent variability in climate, soil and topography, appropriate assessments of yield variability to make more informed decisions require at least several years of data[10]. New methods of analysing spatial-temporal data from satellites or yield-monitor data from farmer machinery can produce yield stability

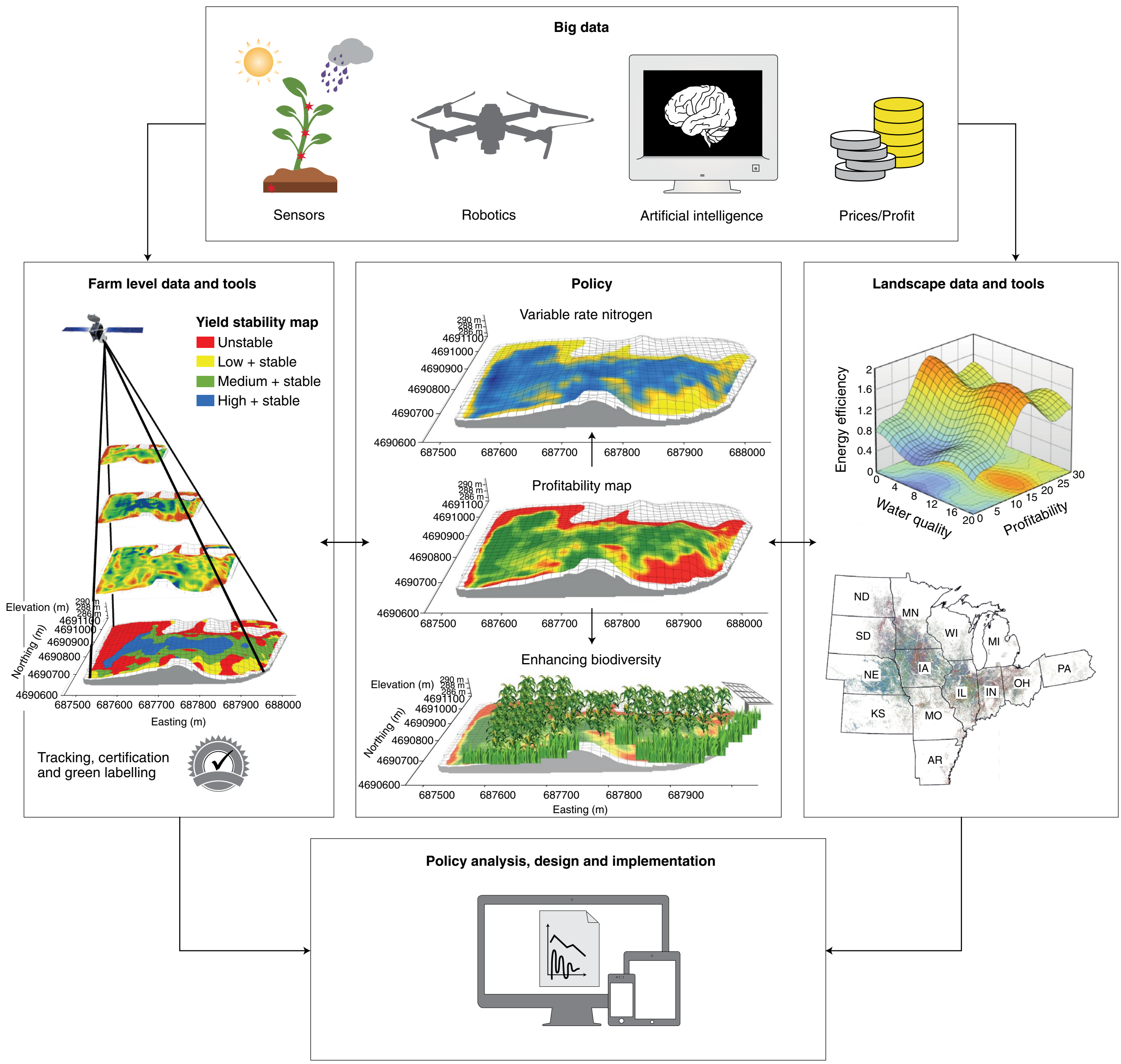


**Fig. 1 | DA in agricultural systems.** DA can be used to design and implement sustainable agricultural systems at farm and landscape scales.

maps that can be integrated into farm- and landscape-scale data systems (Fig. 1)[10]. Yield stability maps depict areas within a field characterized by consistently high productivity over time, other areas with consistently low productivity, and other areas where yields are unstable — high one year, low the next. With use of stability maps, DA can help re-design fields or subareas within fields that are unprofitable or environmentally unsustainable, and sustainably intensify high-yield areas of the field knowing that these can respond to more inputs (Fig. 1). Analysis shows that if N fertilizer applications were based on plant N demand from different yield stability classes, N use in the US Midwest could be reduced by as much as 36% (or 65 kg ha$^{-1}$) compared to current, uniform applications. Co-benefits include net energy savings of 3,200 MJ ha$^{-1}$ and a reduction in greenhouse gas emissions from the unused fertilizer of 890 kg $CO_2$e ha$^{-1}$. DA could also enhance sustainability by helping farmers efficiently diversify their farms. Subfield areas with low input response could be allocated to biodiversity-conservation strips[11], agrivoltaics[12] or to perennial bioenergy crops[13]. Furthermore, the accumulation and recycling of plant available nutrients by these native prairie strips encourage improvement of the low stability zones. In the presence of supportive policies and markets, perennial bioenergy crops planted on low yielding stable zones could generate 3,000 l ha$^{-1}$ of ethanol, on average, equivalent to 23 MJ l$^{-1}$, for a total potential energy production, if implemented on 40 million ha of corn in the United States, of ~0.7 EJ (exajoule).

Thus, DA shows the potential for improvements in the sustainability of agricultural systems both through more efficient intensification where responsive (referred to by some as 'sustainable intensification')[5], and also through diversification and increased presence of biodiversity (crops, pollinators, animals and so on) in areas where current systems have shown to be unprofitable or harm the environment.

The complexity of agricultural systems and the multi-faceted nature of sustainability mean that two steps will be needed to move agricultural systems towards more sustainable pathways[14]. First is a design step that involves participatory processes to select indicators and set goals, and uses geospatial data analytics and modelling tools to quantify outcomes, balance competing interests and create political support for solutions. Second is an implementation step that involves public and private investments in more sustainable technologies such as DA, as well as demand-side and supply-side policies such as taxes or subsidies that incentivize or otherwise appropriately encourage changes in the behaviour of consumers and producers[14]. DA is capable of tracing sustainable practices and linking them to consumer products to develop sustainable certification labelling. Sustainable technologies need to be developed that are economically viable for the large-scale industrial systems as well as ones that are appropriate for smaller-scale systems in the developing world[15]. Smallholder farmers are applying digital technologies to learn new skills, connect themselves across wide areas, receive and deliver services. Throughout the world, new businesses are emerging to provide farm management support, yield analytic capabilities and access to financial capital from investors[15]. An outstanding challenge is to find ways to make the technologies more scale-neutral so that they can be utilized by both small- and large-scale operations. This is another area where public policy could play a positive role to support development and adoption of more sustainable technologies.

As the struggle for implementation of effective climate policy over past decades has shown, the complexity of modern economies and societies creates great political and governance challenges to sustainable development. There is now widespread recognition that the global food system must change to support the goals of sustainable development, and much progress has been made towards understanding the kinds of changes in production and consumption of food that may be necessary[16]. Yet, thus far there have been many pronouncements of what 'must' change, by scientists as well as by advocates with particular economic or political interests, but little discussion of how those changes can or should be implemented in ways that balance the economic, environmental and social dimensions of sustainable food production. In our view, until society makes the needed investments in science-based, participatory processes to map out realistic and equitable options for achieving sustainable development goals, progress will remain limited. The political and governance challenges of implementation remain daunting everywhere, with distinct challenges facing the developing and industrialized countries. The good news is that the tools such as digital agriculture needed to design and implement more sustainable agricultural development pathways for both developing and industrialized countries are advancing rapidly. Although the challenge remains daunting, progress is possible as citizens, businesses and governments throughout the world recognize the imperative of sustainable development. ❐

Bruno Basso[1,2]✉ and John Antle[3]

[1]*Department of Earth and Environmental Sciences, Michigan State University, East Lansing, MI, USA.* [2]*W.K. Kellogg Biological Station, Michigan State University, Hickory Corners, MI, USA.* [3]*Department of Applied Economics, Oregon State University, Corvallis, OR, USA.*

✉*e-mail: basso@msu.edu*

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## Competing interests

The authors declare no competing interests.