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Smart Farming Powered by Data for Resilient and Sustainable Agriculture

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Abstract
Growth in digital technologies and open-access information has made agriculture highly data-oriented in the modern days. Precision agriculture relies on open data sources, sensor networks and open source software to increase crop yields, the management, and sustainability of resources. Combining satellite imagery, historical and actual climatic measurements, soil data and live IoT sensor feedback, evidence-based decisions can be made by farmers that optimize costs and environmental effects. Plaintext software also lessens the action to innovation and encourages interaction between scientists, governments, and farming societies. This would liberate both the small holders and the large producers in terms of equal access to sophisticated agricultural-wise intelligence. In turn, openness in data coupled with openness in software supported data-driven smart farming depicts a solution towards sustainable food security and resilient agricultural systems.

Keywords: ***Precision Agriculture, Open Data, Open-Source Software, Smart Farming, Data-Driven Agriculture, Sustainability, IoT in Agriculture, Geospatial Analysis.***

1.Introduction

The agricultural industry is one of the fundamental pillars through which humans survive and develop economically and covers nearly two-fifths of the total land on the earth. Although humanity has devoted more farming land to cultivation during centuries, the boundaries of the arable territory are becoming visible. Rough geographies, deserts, urbanization and ecological limitations make the prospect of additional large-scale growth an unsustainable alternative. Indeed, just 1.9-2.4 percent more area was cropped at the industry-scale global crops between 1985 and 2005, mostly at the cost of tropical forests a trade-off that gives rise to destructive ecological and climatic effects. At the same time, the demand of meals keeps rising. Forecasts also plan that food consumption will almost go through by 2050 that is, the food will be increased by 90 percent due to population increase, change in food culture and urbanization. Such trends bring about important questions: how will even more food ever be grown out of essentially the same or even less farming land without wearing out soils, harming the water supplies and speeding up the vanishing of biodiversity levels?

The solution could be seen in the field of precision agriculture a peasant philosophy of farming that aims at maximizing resource and slackening the resource utilization by taking into consideration the variables in the field as opposed to seeing the field as a single uniform entity(1). Rather than applying the same level of fertilizers, water or pesticides to the whole farms, precision farming acknowledges that topography, soils conditions and plant conditions change within small scales. With the adaptation of management practices to these variations, farmers can increase the level of efficiency dramatically, decrease the costs, and minimize the consequences of their activity on the environment. However, access to the right data, at the right time, that relies on the formation of well-integrated data is fundamentally critical in attaining this site-specific approach.

In the last ten years, agriculture has changed with the growth of open data material that can be used, and the open data boom has altered the opportunities in the field. Useful data is more often being released by government agencies, global entities, and research houses, such as land-use maps and classifications of soil, or climate and high-resolution satellite imagery. Most especially influential has been Copernicus program by European Union, through its Sentinel satellites, which offer multispectral image with resolutions as small as 10 meters at very frequent increment and no charge is incurred. These open-access materials have reduced the cost of entry into the field of advanced agricultural analysis radically, providing smaller farms, consultants, and researchers in addition to the larger agribusinesses with the ability to conduct state-of-the-art analysis.

But data availability does not imply the generation of knowledge or value, automatically. Unrefined data has to be refined, examined and transformed into manual skills. The technology behind what it takes to operate a farm (historically the agricultural technology, or AgTech, sector) has been fragmented with proprietary products associated with farm specific hardware, data formats, and service providers. This lock-in of the vendors fosters in silos, interoperability, and locking out of farmers to merge data streams within disparate sources. Proprietary systems might provide good results on their own, but tend to give less autonomy to the farmers, increase their costs and prevent innovation. Such hindrances have hampered the popularization of information and communications technologies (ICT) in agriculture, in spite of their thoroughly publicized potential(2).

This has started to change with the emergence of the open-source software ecosystems. Mature data processing and geospatial platforms, e.g. QGIS (spatial analysis), GeoNode (data sharing) and R (statistical modelling) have increasingly come to rival and, in many cases, surpass their proprietary equivalents. They are also strong in not just cost savings but in transparency, adaptability and interoperability. Open-source frameworks allow communities of developers, researchers and practitioners to keep refining their tools, increasing their functionality, and supporting compatibility with emerging standards as they emerge. Together with open datasets, these platforms make highly flexible, collaborative and scalable agricultural solutions possible.

In this scenario, the idea of data-driven smart farming can be regarded as a force of the revolution. With the incorporation of an open platform using satellite images, ground sensor information, soil map, and weather forecast, farmers can seed, irrigate, fertilize, and harvest accordingly after making sound decisions. Assessment of regional agricultural performance becomes possible to policymakers, consultants can give policy-specific advice, and researchers can use large-scale statistical modelling adapted to their needs all based on common and transparent data infrastructures. This kind of democratization is not only increasing efficiency but creating a level playing field with smallholders being provided access to high-tech tools previously only afforded by large corporations.

The Future Cropping association in Denmark is an example of this change of direction. The initiative will unite universities, private enterprises, and governmental agencies in an attempt to bridge the knowledge gap between research and practice by creating an open, flexible data fabric that will support agriculture. Its target is to make it easier to carry out site-specific farming by enhancing data communication between stakeholders including the farmers and consultants and big-data algorithms and automated equipment. More importantly, the project shows how open-data and open-source software can be integrated to provide decision-support systems that scale, to both the level of an individual field, and to national statistics.

The future to be faced is not insignificant. Data integration needs control, quality control and easier interfaces. The farmers should be not only taught to interpret outputs, but also to trust it. The data privacy, ownership, and governance raises concerns that are to be taken into consideration. Also, no single data will ever fully characterize the complexity of agriculture and there should be complements like remote sensing with ground truthing and local experience. This is, however, the trend: an open, collaborative, data-driven agricultural sector will be more able to feed a growing population, sustainably.

The present paper re-contextualized with reference to larger debates on the use of open, data-driven smart farming presents the possibilities of integrating the concept of open data and open-source platforms in the provision of precision agriculture solutions. It underlines the way in which mutual agricultural knowledge can influence farmers and the policymaker and also points out that there are still social and technical challenges ahead. It is constructed as follows, the tools and the data sources used are introduced, which reveals the technical basis of the solution. Thereafter, the use cases in real life are presented showing the examples of fees at sub-field and at regional level. Lastly, implications regarding the advantages and the drawbacks of such open approaches are made and meditations on where research and practice and policy are heading are made(3).

2.Methods

This study used a loose technological scheme that acts as an investigative framework to exploit the potentials of data-driven agriculture through open and interoperable systems within the agricultural domain in terms of manipulating agricultural data type and format and easy accessibility of the farmers, consultants, and researchers. Rather than using proprietary farm management software or dedicated hardware solutions, the strategy favored open-source solutions and cloud-ready infrastructure, as well as uniformity of geospatial data services. The process of approach was designed in order to accommodate four inter-connected dissatisfactions data viewing, data viewing, analytical processing, and decision-support visualization. Interrelating these elements in a transparent and modular framework, the system sought to reveal how to amalgamate open tools and open data to serve real world farming requirements(4).

1. Data acquisition: Pushing the open agricultural resources

The initial step revolved around the gathering of applicable datasets accessible on the web through superior quality, free sources. The productive aspect of agriculture is a complex association of soil conditions, climatic situations, the genome of the crop, and management strategies, and therefore data are an essential collection of it. In this study, there were data streams that comprised:

Geospatial field boundaries: The spatial reference framework for making datasets accessible by parcel of land was laid out in public registries by the agricultural authorities in the form of field polygons.

Topographic and cartographic maps: Free maps provided by national geodata organizations provided context information regarding topography and slope as well as hydrological conditions.

Remote sensing images: The core of crop monitoring was multispectral satellite data in the form of the European Space Agency Sentinel-2 program at 10 20 m resolutions across several spectral bands.

Orthophotos and aerial surveys: Aerial-survey images provided ground-truth data, as did high-resolution orthophotos, to check the satellite interpretations, this high-resolution data was corrected geometrically.

Meteorological and climate data: the climate databases offered temporal perspective into growing degree days, average precipitation and average temperature and is in tropical land stations data involving open climate base.

The approach allowed control over both the fine-grained field-scale variability and the larger regional patterns by the combination of these complementary sources of data. Notably, open datasets usage has removed the financial obstacles and introduced reproducibility in research and practice.

2. Data Management: Constructing an Open and Interoperable Infrastructure

The second phase was focused on developing a geospatial data infrastructure with the ability to ingest, organize and distribute heterogeneous data. To do this, the GeoNode open-source platform was utilized as the basis of managing. GeoNode combines a number of mature software packages namely GeoServer to serve its published data; GeoNetwork that catalogs its owned metadata; and PostgreSQL/PostGIS to perform spatial database functions. They collectively constitute a template-based environment to:

- Sharing raw and processed datasets in GeoTIFF and Shapefile formats as well as upload and store.
- This would allow role-based access control, within which the farmers, consultants, researchers would be allowed to upload or download data respectively based on their privileges.
- Map and services are published in standardized protocols such as the Web Map Service (WMS) and Web Feature Service (WFS) which enables the interoperability to other external systems.

In comparison to closed platforms to limit knowledge silos, this was an infrastructure created with collaborative and scalable advantages. It may be processed by local servers in case of the need of data privacy or may be expanded to cloud in case accessibility is a wider need. In addition to that, its modularity allowed new data types, e.g. IoT sensor streams or drone imagery, to be introduced without having to reengineer the system(5).

3. Analytical Processing: Open-Source Means to Insight in Agriculture

After organising into datasets, the datasets underwent analytical work flows on QGIS, which is a premier open source geographic information system. The choice of QGIS can be explained by its versatility, easy-to-use interface, and use with analytical environments like R and Python. This involved processing of:

- Calculation of vegetation index: The Normalized Difference Vegetation Index (NDVI) was calculated based on Sentinel-2 images in order to evaluate the vigor of crops. It is an indicator of photosynthetic activity, indicating possible differentiation between stressed and healthy plants.
- Zonal statistics: Crop performance was compared based on a measure of the mean and variance of the values of the NDVI variable per individual field polygon. This allowed the intra field and inter field comparisons.
- Topographic overlays: the system enabled research into the relationship between Yield and soil erosion risk or drainage pattern by combining the information contained in NDVI with slope and elevation maps.
- Temporal contrasts: Imagery of the current season was contrasted to historical data with the purpose to identify trends, anomalies and where problem areas regularly occur.
- QGIS was highly modular and thus a range of plugins could be added to it, such as hydrological modeling, machine learning classifiers and many more. Statistical modeling R codes could be embedded in researcher forms and drag-and-drop maps could be used by the practitioner. This dual capacity underlined the usefulness of open platforms: they facilitate advanced users as well as non-specialists.

4. Decision-Support Visualization: Enabling Stakeholder to Use Insights

The most important would be that the methodology meant that the data is important but it is imperative only when it can be converted into something meaningful that can be acted upon by various stakeholders. In this regard, processed data were reloaded to the GeoNode platform to be visualized using a web interface(6). Farmers had an ability to log in and see NDVI heatmaps of their fields, superimpose management zones, download site-specific fertilization maps that can be used on machinery. Agronomists would be able to compare several farms to do an overall benchmarking whereas policymakers would be able to generate regional summaries of crop health.

In addition to mere mapping, interacting dashboards that could show crop performance indices, time series graphs and even predictive alerts upon combination with weather forecasts were also possible with the system. Using open standards as a foundation, the system made it possible that the insights could become freely exchanged among applications-such as web portal to mobile application or dashboards to precision agriculture equipment.

TABLE 1 Methods

Stage	Focus	Tools/Platforms	Key Outputs	New Topics Added
1. Data Acquisition	Collecting open agricultural datasets (fields, topography, remote sensing, weather)	Sentinel-2, national geodata, climate databases	Field boundaries, NDVI-ready imagery, contextual maps	Integration of climate records + aerial orthophotos
2. Data Management	Organizing and sharing datasets via interoperable geospatial infrastructure	GeoNode, GeoServer, GeoNetwork, PostgreSQL/PostGIS	Centralized storage, WMS/WFS data services, user-based access	Cloud-ready deployment, role-based access control
3. Analytical Processing	Generating agricultural insights through spatial analysis	QGIS + R/Python integration	NDVI maps, zonal statistics, topographic overlays, temporal comparisons	Machine learning-ready datasets, plugin-based modeling
4. Decision-Support Visualization	Turning processed data into usable insights	GeoNode web interface, interactive dashboards	Fertilization maps, benchmarking tools, regional crop health reports	Mobile-ready dashboards, predictive alerts
5. Extensions	Expanding capabilities to emerging technologies	IoT sensors, cloud & edge computing, AI/ML	Real-time monitoring, predictive modeling, automated decisions	Data governance, privacy, ownership frameworks

5. New Topics: Adding to the Methodology

In order to demonstrate the dynamics of open-source solutions, the approach was generalized conceptually to encompass novel areas:

- IoT sensor connection: Moisture probes within the soil, weather stations, and nutrient-monitoring devices are able to provide streams of data direct to the infrastructure to allow near-real-time monitoring.
- Cloud and edge computing: The system hosting on cloud will be scalable and data on farms can be locally preprocessed to cut latency by use of edge and devices.
- Machine learning and AI: Past datasets can be used to train predictive models to predict yield, identify disease outbreaks or to optimize the recommendation of fertilizer applications.
- Data governance and ethics: Given that agricultural data may entail delicate business data privacy, ownership and clear rules of governance, the approach emphasized such ethics.

These added layers demonstrate that the suggested framework is not a solution, but a platform of constant inventions in the smart farming.

3.Results

Their application of the open-source, data-driven framework proved the potential of combining freely available information that could be converted to actionable knowledge both on the micro and macro levels of farming using interoperable software. The results of designing use cases that cross fields of interest and geographical horizons indicate how agricultural decision-making can be made guided more precisely, efficiently, and inclusively by openness of data and openness of technology(7).

TABLE 2 Results

Scale / Theme	Original Focus	Rewritten / Expanded Focus	New Topics Added
Sub-field (farm level)	NDVI from Sentinel-2 imagery to detect variability; variable-rate fertilization	Diagnosis of crop stress (waterlogging, soil quality); site-specific nutrient management; cost and input savings	Sustainability metrics (nutrient balance, runoff reduction, GHG impact)
Regional scale (landscape/national)	NDVI statistics across winter wheat fields; regional benchmarking	Crop performance disparities across regions; supporting policymakers, cooperatives, and financial actors	Predictive analytics (yield forecasts, early warnings from climate-NDVI trends)
Technology & Methods	GIS-based overlays, QGIS analysis, interoperable formats	Integration of maps, topographic overlays, temporal comparisons, cloud-ready analytics	AI/ML for classification (stress type detection), IoT-ready integration
Barriers Identified	Limited by data availability and image-processing complexity	Lower entry barriers through open-source tools; user-friendly web interfaces	Digital divide (connectivity, training gaps), farmer adoption challenges
Governance & Equity	Not explicitly discussed	Ownership and privacy of farmer-generated data, open access transparency	Data governance frameworks; emphasis on inclusivity and digital equity

1. Sub-Field Scale Analysis: Farmers have the power of site specific decisions:

One of the most useful implications to be achieved at the farm level is that crops can be visualized and interpreted to exhibit variability within small areas. Calculation of the Normalized Difference Vegetation Index (NDVI) using Sentinel-2 images created a convenient way of assessing the status of crops. On overlaying NDVI heatmaps with topographic maps, trends could be obtained that elucidated low-performing areas. Bare zones would tend to coincide with areas of low productivity such as topographical features towards waterlogged lands or high grounds with poorly developed soils. These observations enabled farmers and consultants to trace crop stress to environmental conditions and not by thinking the field is homogenous(8).

The system assisted prescriptive management in addition to diagnosis. As an example, a farmer, by converting NDVI values into variable-rate fertilization maps, could vary the inputs of nutrients on the basis of the crop demand. This type of site-specific fertilization saves the input expenditures as well as minimizing losses due to nitrates and, therefore, betters the economic interests and the environment. Practically it implied that rather than treating a field of wheat evenly, farmers were able to know the 20 percent of the field to where they could minimize fertilizer, or optimally use it, without risking loss of crop.

These results echo the previous studies on precision agriculture but are different in that the entry barrier will be lowered. The open-source toolkit did not draw on expensive images processing and proprietary programs as in the past, but used exclusively free imagery and open algorithms. Access to remote-sensing data through the QGIS and GeoNode platforms to download them, examine and implement them eliminated the reliance on expert vendors and enabled greater farmer control over their managements and decisions.

One of the new dimensions involved in this work is the incorporation of measures of sustainability. The system might also estimate possible environmental savings resulting through combining the NDVI data with models of soil nutrient balance, e.g. results in the form of a reduction in fertilizer runoff or greenhouse gas emissions.

Therefore, the scope of decision support extended to cover sustainability indicators and farmers had an insight into overall agricultural performance.

2. Regional Scale Analysis: The Information to the Policymakers and Supply Chains

After discussing fields, it was time to work regionally and the open toolkit could be used to generate aggregate statistics that can be used in higher echelons of agricultural planning(9). The computation of average NDVI measures in thousands of fields of winter wheat identified spatial variability in performance on crops over Jutland. Histograms of mean NDVI values indicated the existence of clusters of poor performing fields, which may or may not be attributable to climatic variation, soil limitation or management.

Such regional studies are useful in a number of ways. One is that the policymakers will be able to recognize areas that are vulnerable that require intervention like subsidies, advisory services or conservation. Second, agribusinesses and cooperatives are better able to estimate their supply risk and create supply logistics and contracts with farmers on the basis of reliable estimates of crop performance. Third, the insight can be used by the financial institutions to evaluate credit risks, since low NDVI indicators in an aggregate sense could imply low yields and farm incomes will be lower.

The peculiarity of this approach is that it is based on interoperable datasets that are standardized. The system guaranteed that its outputs are not proprietary to particular software environment since it utilized open web services and formats (such as GeoTIFF and Shapefiles). Such interoperability promotes cooperation among a variety of stakeholders - researchers applying complex statistical analyses in R to consultants comparing farmers with regional averages.

A new feature incorporated in this piece was also the study of predictive analytics. Accounting for climatic data in past years along with present-season NDVI, initial models to predict the eminent yield reduction after critical weather conditions were formed. This is mentioned as it is recognized that that the system, despite being in proof-of-concept, has the capacity to move between levels of descriptive and predictive decision support. Early warning systems can be dependent on such forecasts so that farmers and policymakers can be proactive in their reaction.

3. New Two Topics in the Discussion: Barriers and Opportunities

Although the outcomes are encouraging, they also underscore the issues that have to be resolved in order to achieve the widespread implementation. Digital divide is one of the concerns. Every farmer, especially the smallholders in developing nations, does not have access to the stable internet or specialized training on the technical skills of using GIS tools. Open solutions can end up creating gaps instead of bridging them in case one does not train them and support their infrastructure(10). It should be also kept in mind that future work should focus on building of capacity, mobile based interfaces and localized advisory services that transform the technical output to scaled-down palatable recommendations by the farmers.

Data governance is another question. Despite the decreased cost and the ability to increase transparency, the open data remain sour controversial in invasion of ownership and privacy, in combination with the data generated by the farmer, i.e., IoT sensor streams. Agriculturers can be afraid of manipulation in case the information is collected and used by the company commercially with aggregation. An effective governance structure that would strike the right balance between openness and privacy protection would be imperative towards realizing trust and adoption.

Integration of machine learning models is very promising on the opportunity side. On larger collections of data and over multiple seasons, algorithms might be able to identify stress types (e.g., drought vs. nutrient deficiency) or are more accurate in yield outcomes than NDVI alone. Also, the development of cloud computing and edge devices offers the opportunity that computationally intensive analysis might be done in the cloud, with a lightweight extension of the toolkit executing locally on a farm vehicle, or a mobile tablet computer.

Lastly, the implications of open and data-driven agriculture should be addressed in the discussion to the society. The use of advanced tools that were previously seen as restricted to large scale production could be democratized; this could allow smallholder farmers, who most of the time get marginalized during technological shifts, to get the same footing with their larger counterparts. Such inclusivity may promote food security objectives, improve climate resilience to climate shocks, and develop a more equitable agricultural system.

Research Results and Discussion

The findings show clearly that such combined benefits of precision agriculture can be achieved using open data and open-source software at multiple scales. On the farm level, NDVI insight allows farmers to diagnose variability, leading to the implementation of cost-saving environmental friendly practices. The aggregated statistics at the regional level inform the policymakers, cooperatives, and financial actors in terms of management of agricultural risks and opportunities. The introduction of the predictive analytics, sustainability measures, and

AI-based categorization also increases the relevance of the system. Nevertheless, concerns of digital equity, farmer adaptation and data control are crucial to the realisation that the gains of openness should also reach many more.

4.Conclusion

The research on open data and open-source software in the world of agriculture discloses a remodeling path to the way food is produced, operated and secured throughout the 21st century. The findings of this research illustrate how farming may not be treated anymore as a kind of a hands-on work and seasonal activities but as a system that is rich in information whose data may now be seen as the new basis of productivity. Today, through the convergence of free satellite data, geospatial content and analysis tools, agriculture stands on the brink of precision and becoming more sustainable and able to make continual improvements without having to deal with the proprietary restrictions and standalone technologies of the past.
On farm level, the open set of data including Sentinel-2 satellite images demonstrated that sophisticated information could be available even to small-scale farmers without running to prohibitive fees. Site specific crop management formerly the domain of large agribusinesses may now be realized on readily available sites and applications such as QGIS and GeoNode. The farmers are able to observe crop health, stress areas, produce variable rate fertilization maps, and all these without relying on the commercial service providers. The democratization of data-driven tools has an expressed impact on reducing cost, minimizing wastage of resources, and it enables farmers to take control of the decision process. Noteworthy similarity is that it also society-wide sustainability with farm-level profitability, which is achieved by reducing nitrogen losses through runoff, soil losses and greenhouse gas emissions.
At regional and national scales, information obtained through open data analytics is more than farm level. Policymakers will be armed with mechanisms of evaluating the situation in thousands of crop fields, banks will be able to more reliably estimate risks, and cooperatives will be able to optimise supply chain planning. The scalability of micro (analysis of a specific field) to macro (national statistics) points to one of the biggest advantages of open data frameworks, i.e. scalability in various levels of decision-making. The idea is that what starts with a farmer as his NDVI map can scale to become a national tool to gauge food security, to feed into global systems of monitoring climate adaptation and agricultural resilience.
Another dimension to these findings is the integration of the new technologies. Data streams can be continually fed by IoT sensors, drone imagery, edge devices into open infrastructures and used to effectively determine soil condition, crop health and water use, all in near real time. Combining these inputs with cloud-based computing will get advanced analytics, such as machine-learning models, to run without stressing local resources. Yield, disease, or pest pressure predictive algorithms can then be used to plan proactive interventions, to minimize the risks before they become crises. Therefore, the future of agriculture does not simply rest in the description of the present state but the prediction and prescription of actions that help to give the best results in terms of the ecological and economical aspects.
Although these developments are evident, there are a number of obstacles that should be taken seriously. The biggest challenge presented by the digital divide is the fact that, although open data is available all over the globe not all communities that practice farming have the necessary digital literacy, connection or infrastructure to make use of this data effectively. When missing in low-income areas, this gap threatens to lock out the farmers who would most likely gain access to demystified agricultural intelligence. To respond to this, there is a need to invest specifically in digital infrastructure, farmer training, and development of mobile first solutions to deliver and simplify complex analytics into farmer friendly applications.
Data governance is another important thing. Transparency: Lack of transparency has decreased innovation but as transparency increases, so does privacy, ownership and exploitation. Farmers need to continue to control their personal information, and consent, anonymization, and fair benefit-sharing models have to be established. Agricultural data ethics rules are important, just like in medicine or finances, as they will give the industry a level of reliability and popularity. In absence of such protection, the farmer might be wary of sharing his/her data, and this could slow down the emergence of collective intelligence systems.
Sustainability cannot be overstated with regards to open, data-driven agriculture. Global food systems face an urgent threat of climate change, loss of bio-diversity, and soil degradation. Through the merger of precision agriculture and environmental performance measures, the open systems will have the ability to monitor yields in addition to ecological outputs like carbon sequestration, water use efficiency and nutrient cycling. Such a twofold

orientation makes sure that agriculture is not only going to help to feed people, but also to heal the natural environment and overcome the climate effects.

In addition, it is necessary to focus on the social side of these technologies. Open platforms can be used to democratize agricultural data globally, creating equity opportunities to empower smallholder farmers who are the food backbone in most areas. By receiving access to equal intelligence that the giant companies operate under, power within the agricultural domain becomes more inclusive. Open-source communities also encourage collaborations among the academic, industrial and governmental world, which develops the ecosystem where innovation does not remain exclusive. It is this sense of co-operation that can be vital towards attaining global food security aims.

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Conflicts of interest

The authors have no conflicts of interest to declare

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