

Advances on the Internet of Things for High-Resolution and Multi-Scale Measurements in Agricultural Ecosystems

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Abstract—This article presents an overview of recent advances in sensors and data collection applied to monitoring agricultural ecosystems. It first describes a range of innovative sensors currently under development, at both microscopic and macroscopic scales. Next, it highlights recent approaches to collecting data from these sensors in the field, via wireless and satellite communications and data collectors mounted on autonomous vehicles. An example of data collection by drone is presented in this regard. Finally, several future research directions concerning the Internet of Things applied to agroecology are discussed, with a focus on energy consumption and life cycle. Knowledge of these advances invites us to consider new perspectives in agroecology, but also to reflect on the means and policies that could support farmers to adopt these new technologies on a large scale.

Keywords-Internet of Things; Sensors; Wireless communications; Agricultural ecosystems.

I. INTRODUCTION

Faced with climatic, environmental and demographic challenges, one of the objectives of agroecology - which is a multi-scale and holistic concept (from the plant to the food distribution) - is to develop agricultural ecosystems leading to the preservation of natural resources while generating efficient crop production and positive socio-economic outcomes [1]. To this end, emphasis is placed on significantly reducing the use of chemical inputs by creating conditions conducive to the development of biological diversity and soil fertility. This is achieved through crop diversification and landscape modification as illustrated in Fig. 1. In fact, the spatial and temporal diversification of crops improves agronomic sustainability by limiting pest infestations, reducing disease pressure, mitigating soil degradation and strengthening the overall resilience to climatic variability [2]. Furthermore, rotating crops improves soil fertility and structure, reduces pesticide use by disrupting pest cycles, and contributes to increase biodiversity. These agroecological practices can moreover generate more stable agricultural yields and higher incomes than conventional agriculture [3].

However, the adoption of such agricultural practices remains uncommon on a large scale due to the difficulty of managing highly diversified crops by the farmer. These ecosystems require in fact specific and close monitoring of soil health, plant growth and biodiversity - at both macroscopic and microscopic scales - in order to optimize crop production and detect anomalies early [4]. The Internet



Figure 1. Examples of spatial arrangements fostering biological interactions: (a) Strip intercropping, (b) Pixel cropping, (c) Permaculture.

of Things has thus a crucial role to play in this regard by designing appropriate sensors and developing relevant data collection strategies [5]. As illustrated in Fig. 2, the ultimate goal is to create a reactive closed-loop process: environmental and biological data are collected remotely in the field, then shared in the cloud and combined with human expertise and history of previous agricultural operations to feed databases, models, scenarios and decision-making algorithms. This feedback process aims to improve the biological interactions and crop production over time, while being able to rapidly adapt to perturbations and varying environmental conditions.

However, remotely collecting a wide range of data on several crops at high spatial resolution - in near real-time and at both microscopic and macroscopic scales - poses many challenges. On the one hand, the design of sensors able to measure the state of living soil, the presence of species and the plant health is challenging. On the other hand, the high variability inherent to the spatial distribution of plants requires deploying a significant number of sensors with a high spatial resolution [6]. This creates new challenges, especially in terms of sensor distribution and data collection strategies. These challenges are in addition to the problems of energy consumption, environmental footprint, connectivity in areas without communication facilities and frugality of sensing infrastructures [7]. Recent advances in sensor development, satellite communications, ground and air robotic systems, as well as in edge computing and embedded artificial intelligence, are however opening up new opportunities for meeting these challenges.

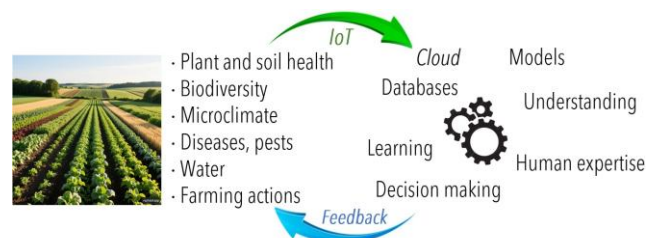


Figure 2. Closed-loop process to adapt farming actions accordingly.

This article presents an overview of recent advances in sensor design and data collection applied to the monitoring of agricultural ecosystems. It is organized as follows. Section II presents a set of innovative sensors currently under development at both microscopic and macroscopic scales. Section III reviews recent approaches to conducting remote data collection in the field, with an emphasis on energy consumption issues. Section IV illustrates a process of data collection using drones. Finally, Section V presents the conclusion and discusses future research directions.

II. SENSORS FOR MONITORING AGRICULTURAL ECOSYSTEMS

Agricultural ecosystems are living systems that are particularly complex to monitor and understand. In order to optimally and sustainably manage the crop production, remote sensing of environmental and biological data is of increasing importance. As illustrated in Fig. 3, this data concerns the soil, the plants, the biodiversity (below and above ground), the climate (global and at the plant level) and the human operations. To collect this data, sensors are the first step in the chain of the Internet of Things. Some are specifically designed to observe the state of living soil and assess the presence of species, others enable to monitor crop growth and plant physiology, whether it be at the microscopic or macroscopic scale. In this Section, we present an overview of particularly innovative sensors currently under development (indicated in red in Fig. 3) in this regard.

A. Measurements at macroscopic scale

1) *Soil monitoring:* The soil provides the structural support, water, and nutrients necessary for plant growth. It is a living ecosystem containing microorganisms, insects and plant roots. Regularly monitoring the soil health is essential for maintaining a sustainable production [8]. Although the metrics are not well established to quantify the soil health [9], some indicators, grouped into biological, physical, chemical, and functional dimensions of soil functioning, are reported in the literature [10].

The current solutions to assess these indicators remain however limited to a few localized and macroscopic measurements obtained from in situ sensors. The main data monitored within an agricultural ecosystem include soil moisture, temperature, pH, nutrient levels, and electrical conductivity [11]. These measurements are collected using probes buried in the root zone and radio antennas are positioned on the surface to transmit the measurements. Alternatively, three other innovative approaches are currently being investigated to collect soil data at high spatial resolution, based respectively on fully buried sensor nodes, biodegradable sensors and sample collection from ground robots and drones.

Fully buried sensor nodes. The development of the concepts of Internet of Underground Things (IoUT) and Wireless Underground Sensor Networks (WUSNs) is a recent paradigm aiming to completely bury the sensor nodes, including the radio components [12]. The main advantage lies in the possibility of positioning them anywhere, including in the path of agricultural vehicles, and therefore of easily multiply them in a field. They are moreover protected against the damages generally suffered by surface radio antennas (e.g., damages due to agricultural implements, weathering, theft). However, as the propagation of the electromagnetic waves is much more attenuated in the soil than in the air, about 20 to 300 times worse [13], several scientific and technological challenges remain to overcome, whether it be in terms of communication ranges (usually only a few tens of meters), data collection and energy consumption. The use of drones is a relevant way to collect data of buried communicating sensor nodes [14].

Field-deployable biodegradable sensors. The development of biodegradable sensors is another innovative strategy. For example, Gopalakrishnan et al. [15] have designed miniature chipless sensors (2 cm²) to monitor the soil Volumetric Water Content (VWC) during seed germination. The sensors are based on miniaturized resonant antennas, constructed from biodegradable materials and compatible with radio frequencies. The resonant frequency of the antenna varies with the soil volumetric water content. The objective is to design sensors able to operate a crop season before being slowly degraded. To collect the measurement, a drone carrying a reader module is used at low flying height (40 cm) to send the interrogation signal and read the reflected signal from the sensor tag. The results demonstrated the capability to measure the VWC within the range of 3.7-23.5%. The final goal is to deploy these sensors at a large spatial scale at 5 cm deep by using a seed drill. Unfortunately, the measurements cannot be stored inside the sensors and depend therefore on the time of drone's passage.

Soil sample collection from robotic vehicles. Performing regular soil sample collections remains, however, the primary method for accurately assessing soil health. This task is, however, time-consuming and does not allow for real-time data. Robots are currently increasingly being studied for collecting soil samples or for moving a probe to different depths in the field [16]. Moreover, as ground robots may have difficulty accessing crops, an alternative is

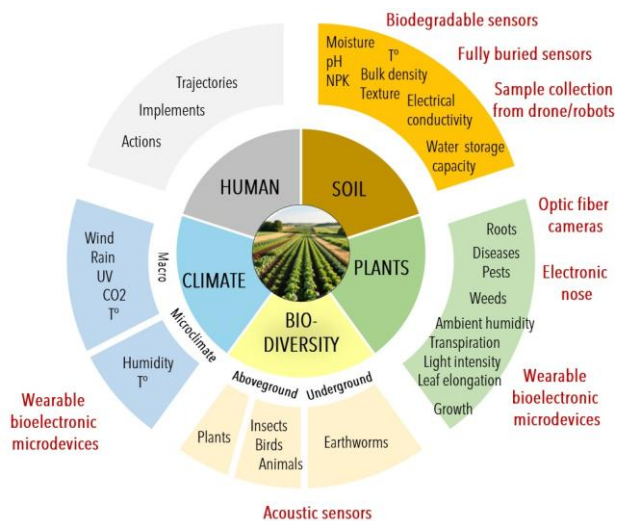


Figure 3. Main data to be monitored in agricultural ecosystems. The text in red indicates recent sensors under development presented in this paper.

to use drones carrying soil sampling tools. For example, Klopfenstein et al. [17] used a rotary-wing drone to collect soil samples of a few dozen grams in agricultural fields. The difficulties, however, lie in the need to apply significant loads to the ground to collect samples, and develop lightweight tools adapted to the maximal drone's payload.

2) *Plant monitoring*: Regularly monitoring the plant health and growth is essential in agriculture, not only to improve crop production but also to understand how some plant varieties acclimate to abiotic and biotic stresses (e.g., climate change, diseases). At the macroscopic level, the monitoring of crops (e.g., yields, diseases, pests, weeds) are commonly carried out through visual observations from satellite images, field sensors or cameras embedded on drones or ground robots [18]. However, more and more approaches are studying the development of other methods to detect diseases and pest infestation early.

Electronic noses for plant disease and pest detection. In fact, with global warming and climate change, invasive pests and pathogens are rapidly extending their territory to new geographic areas and can impact the overall ecological balance of agricultural ecosystems. This proliferation of insects, bacteria, viruses and fungi may have a significant impact on agricultural yields and on biodiversity. The early detection is therefore essential. To this end, electronic noses are particularly promising to detect volatile organic compounds emitted by infected plants [19]. In recent years, research has intensified in this area with ultrasensitive electronic noses and recognition algorithms based on artificial intelligence to identify infestation patterns [20]. The simultaneous presence of multiple diseases complicate however the identification processes, and variability of environmental conditions (e.g., temperature, humidity, wind) may impact the olfactory measurements. For example, Huttnerova et al. [21] demonstrated the possibility of measuring the presence of a substance that identifies bark beetle infestations in forests using ground-based measurements. The electronic nose was then mounted on a drone to fly over the canopy. Despite the installation of a one-meter sampling tube positioned at the front of the drone to minimize the influence of air movements on the electronic nose, the detection of the substance proved unsuccessful. The hypotheses put forward were a lower concentration of the substance above the canopy and stronger winds above trees.

3) *Biodiversity monitoring*: Biodiversity, both aboveground (e.g., birds, insects, animals, plants) and underground (e.g., insects, earthworms, microorganisms), is a major indicator representative of the good health of an ecosystem. In fact, the diversity represents a key element for capacity of pollination, nutrient cycling, pest control, and water filtration. Higher functional and taxonomic diversity enhances agroecosystem resilience, productivity and long-term stability [22]. In particular, insect monitoring is essential in agroecology as these organisms play critical functional roles, including pollination, pest control through natural predation and nutrient cycling. For example, 70% of global food crops depend on insect pollination, making

accurate assessment of pollinator populations a priority for sustainable agriculture. However, traditional monitoring methods, such as pan traps, sweep netting, and visual surveys are labor-intensive, provide limited temporal coverage and often only snapshot data that fail to capture the dynamic nature of insect populations [23]. Recent advances in acoustic technologies propose promising alternatives for continuous insect monitoring.

Acoustic sensors for insect monitoring. Continuous insect monitoring is essential in agroecology to provide the information necessary to assess biodiversity status, evaluate habitat quality, and implement targeted interventions. To this end, the development of acoustic sensors aims to detect and classify flying insects based on their wingbeat frequencies and buzzing patterns. The sensors can operate autonomously for extended periods, collecting data at fine temporal scales that enable detailed analysis of daily activity patterns and seasonal population dynamics [24]. Additionally, acoustic detection methods have proven effective for identifying hidden insect infestations where visual inspection is impractical (e.g., in soil) [25]. The integration of machine learning algorithms with acoustic data facilitates automated species identification and number estimation, addressing the critical challenge of processing large volumes of monitoring data.

B. Measurements at microscopic scale

The design of sensors able to measure the health of ecosystems at microscopic scale is a relatively recent research axis. Some bioelectronic sensors, implantable or attached on plant leaves or stems, are beginning to be studied to collect various information (e.g., ambient humidity, transpiration, light intensity, leaf elongation) and evaluate the plant ability to cope with various abiotic and biotic stresses. At the time being, these studies are limited to controlled environments (e.g., laboratories, greenhouses) but the ambition is to design wearable sensors able to operate on plants growing in their natural environment.

Wearable microsensors on plants. The development of wearable microsensors on plants aim to complement the macroscopic approaches [26]. These sensors must be sufficiently flexible and lightweight to minimize their impact on plant growth. For example, Nassar et al. [27] developed a wearable sensor measuring plant growth using stretchable strain sensors attached to the leaf surface. These strain sensors are capable of measuring the elongation of the leaves at the micrometer scale. They transmit the data via Bluetooth transceivers. Similarly, Zhao et al. [28] developed a multifunctional and stretchable sensor attached to the leaves. This sensor measures variables, such as leaf elongation rates, degree of stomata opening, as well as water content and temperature. The challenge to be met in outdoor conditions is that rain, wind, humidity variations, temperature and light intensity can affect the measurements requiring further research in this regard.

Optic fiber and cameras for measuring root growth. Lastly, fiber optic and visual sensing has been studied to accurately measure the root development of plants. With an

optic fiber arranged in a spiral, Tei et al. [29] managed to measure the penetration of root in the soil. Another approach involves installing a camera inside a transparent tube buried in the ground to measure root growth [30].

Acoustic sensors for underground invertebrate monitoring. In an original way, a few studies aimed to assess underground invertebrate activity and root growth from acoustic sensors. Lacoste et al. [31] for example used highly sensitive piezoelectric sensors to measure acoustic emissions due to the growth of maize roots and the creation of burrows by earthworms. One aim is to monitor earthworm activity periods and adapt the farming practices accordingly to mitigate the impact on the active fauna. Further research is conducted to study the presence of other invertebrates having specific frequency ranges.

III. REMOTE DATA COLLECTION

All sensors presented in Section II must be coupled with wireless communication technologies to remotely transfer the measurements to the cloud. To this end, different strategies can be adopted, depending on whether the sensors are static or can be mobile, see Fig. 4. In the case where the sensors are static, they must either reach a communication element (e.g., gateway, cellular antenna, satellite) or a vehicle as drone or ground robot must regularly come close to them to collect their data. Usually, the communications are based on Low Power Wide Area Networks as LoRa and Sigfox, but also on 3G, 4G, 5G, 6G, LTE-M and NB-IoT, or Wi-Fi, Bluetooth, FSK and ZigBee [32]. Recently, satellite communications based on Geostationary Orbit (GEO) satellites or a constellation of nanosatellites in Low Earth Orbit (LEO) are however increasingly studied for the IoT communications [33]. In fact, this technology is particularly relevant for applications facing signal quality issues or requiring highly reliable global coverage.

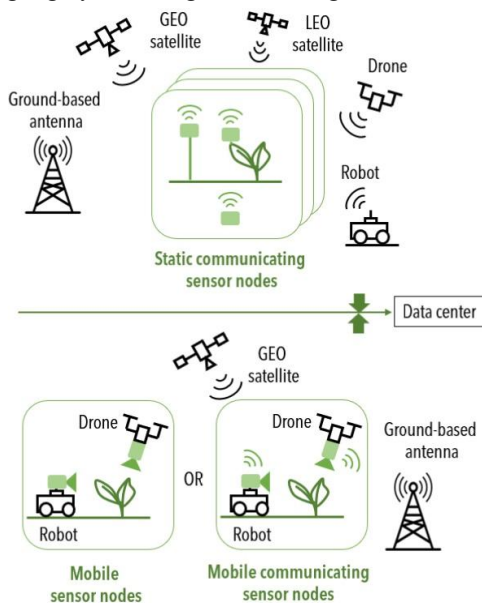


Figure 4. Strategies to collect field data from static and mobile communicating sensor nodes.

Unfortunately, the installation and maintenance costs of static sensor nodes, as well as communication subscription costs, can be a significant obstacle if a large number of sensor nodes need to be deployed. A second issue is the energy consumption of the nodes.

A current challenge is indeed to develop wireless sensor nodes able to operate and communicate with extremely low energy. Low consumption processors, predefined activity schedules or wake-up modules are studied. In particular, by adding an auxiliary Wake-up Receiver (WuR) consuming near-zero energy, the radio frequency spectrum can be continuously monitored for a predefined wake-up signature [34]. When the signal containing the wake-up signature is detected (e.g., sent from a drone), the IoT device in sleep mode is woke-up and its radio activated. This approach aims to highly decrease the node's energy consumption and prolong their operating duration. Another way to reduce the energy consumption of IoT systems lies in local data processing (edge computing). Instead of continuously transmitting raw measurements, sensor nodes can perform preprocessing and transmit only relevant information or alarms. The recent developments in Energy Harvesting (EH) are also particularly promising to supply or recharge self-powered IoT nodes, and even eliminate the need for batteries, see [35]. The energy sources which can be exploited are the ambient ones (e.g., solar, wind, thermal, radio frequency), but also other sources as mechanical ones (e.g., motion of plants) and bioenergy (plants are used as energy sources). For example, the radiation of the frequencies used by telecommunications (i.e., from 3 kHz to 300 GHz) can be harvested to generate a few microwatts sufficient to supply ultra-low-power IoT nodes, see [36]. The exploitation of plant motion is also an interesting strategy to harvest energy. For example, Meder et al. [37] aim to harvest the energy of artificial leaves installed on real leaves by exploiting their motion and oscillations due to wind. Bioenergetical approaches uses the friction of plants, when they come into contact and separate, to exploit the generated electric charges and develop a triboelectric nanogenerator, see [38]. The development of such new energy harvesting technologies is particularly promising for future sensor nodes in agriculture, requiring however to meet several challenges in terms of quantity of energy produced, conversion, storage and consumption.

Some sensors can also be directly mounted on vehicles which can be connected to a communication infrastructure during the data collection. Otherwise, the data is temporarily stored on the vehicle and will be downloaded once back at the farm's docking station. The vehicles (e.g., drones, ground robots) are in charge to displace the sensors within the fields. This mobility is particularly interesting as it is not necessary to excessively increase the number of sensors in the plots (i.e., the same sensor is used several times). Furthermore, other operations can be performed at the same time by the carrier vehicle (e.g., taking soil samples). This approach requires however overcoming many scientific and technological challenges, whether it be in terms of trajectory planning, control, manipulation and connectivity due to dynamic topology and variable network coverage.

IV. DATA COLLECTION BY DRONE

To illustrate a data collection process from static communicating sensor nodes within agricultural ecosystems, this section presents our latest results on this subject. We recently developed communicating sensor nodes which can be buried at 30 cm depth before being fully covered by soil, see Fig. 5. These sensors regularly measure soil moisture and temperature and transmit this information in LoRa 868 MHz through Underground to Aboveground (UG2AG) communications [39]. By using a data receiver mounted on a drone, the objective is to successively approach each node to activate it from a WuR, and then collect data while



Figure 5. Data collection of buried sensor nodes by using a drone based on RSSI level: (a) Communicating sensor node buried at 30 cm depth before being covered by soil, (b) Drone used to collect the data.

maintaining a high-quality signal (i.e., high value of RSSI). Experiments have shown that the best communications (and therefore data collection) are observed when the drone is positioned directly above the node (RSSI levels greater than -110 dBm). When the drone moves laterally, the RSSI level drops sharply near the ground. However, this strategy poses several challenges, particularly with regard to flight autonomy, optimal trajectory, adapting collection time to the amount of data to be retrieved, and obstacle avoidance by the drone at low flying height.

To enable the installation and removal of sensor nodes, allow rapid deployment across different study sites, and promote hardware reusability, another approach currently investigated is to use a drone equipped with a cable manipulation system to install and move sensor nodes in the field. This approach, similar to drone delivery, brings flexibility but presents numerous challenges in terms of gripping, control and stability.

V. CONCLUSION AND FUTURE WORK

Faced with climate change and the need for sustainable agricultural production, farming methods must adapt and gradually evolve towards greater biological interactions, the preservation of soil fertility and natural resources. New technologies must adapt to these new modes of production by developing efficient sensors and means of collecting data in the field at both high spatial resolution and multi-scales.

Original sensors are currently being developed for this purpose - at microscopic and macroscopic scales - whether they are biodegradable, wearable, or able to detect some odor or sound patterns. To collect the data, different strategies are being studied, ranging from communication with nanosatellites, the use of autonomous drones or ground robots, manipulation of sensors by drones or fully buried approaches. A major challenge is moreover to minimize the energy consumption of sensors and data collection systems,

in particular by finding ways to activate them intelligently and harvest energy from different ambient sources.

The ecological impact of the developed solutions requires also to be carefully studied as early as possible in the design and implementation. The consideration of the life cycle of the approaches proposed is in fact essential, necessitating to analyze all the process, from the manufacturing of the different components to the end-of-life with the electronic wastes. A particular attention must also be paid to modular designs, to be able to replace only a part of a device instead of all the system in case of breakdown or need of evolution. There are several ways of development in the IoT sector serving agroecology, making this research particularly captivating and promising.

The adoption of these advances by farmers also raises other challenges, such as the development of specific policies, common standards, and appropriate training. It is therefore necessary to adapt support systems accordingly in order to move towards a fully data-driven agroecology.

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