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Ramil Brick, Elisa S.; Holland, John; Anagnostou, Dimitris E.; Brown, Keith; Desmulliez, Marc P. Y.

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Spain
Manoj Kumar Jhariya,
Sant Gahira Guru Vishwavidyalaya, India

*CORRESPONDENCE

Elisa S. Ramil Brick,
esr1@hw.ac.uk

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A review of agroforestry, precision agriculture, and precision livestock farming—The case for a data-driven agroforestry strategy

Elisa S. Ramil Brick^{1*}, John Holland², Dimitris E. Anagnostou¹, Keith Brown¹ and Marc P. Y. Desmulliez¹

¹Institute of Sensors, Signals and Systems, School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, United Kingdom, ²Hill & Mountain Research Centre, Scotland's Rural College (SRUC), Edinburgh, United Kingdom

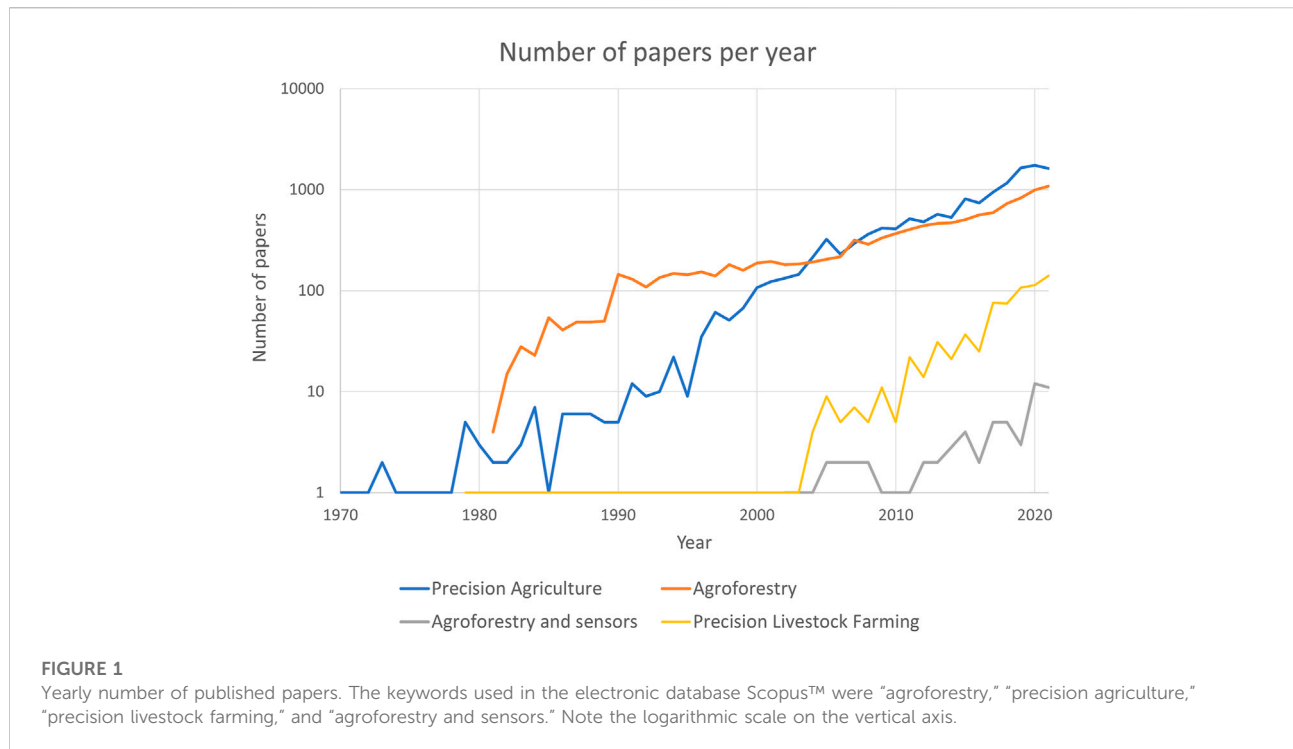
Agroforestry can be defined as an agroecosystem whereby soil is used holistically and synergistically by various stakeholders including farmers, livestock, and plants. As such, agroforestry offers numerous benefits that include conservation of biodiversity, regulation of pests and diseases, increased quality of soil, air and water, efficient cycling of nutrients, and resilience to climate change. Review of published studies in agroforestry shows however that research in this area could benefit from increased real-time, spatial and temporal measurements. This situation is to be contrasted with that of precision agriculture in monocultures and precision livestock farming where progress made in sensor systems has attracted considerable research interest. It is advocated in this review article that wireless sensor networks could also significantly impact agroforestry through the monitoring of the local real-time interactions that occur between the various components constituting agroforestry systems. This review article proposes therefore the new field of data-driven agroforestry which lies at the intersection of precision agriculture, precision livestock farming, permaculture, and agroforestry. Data-driven agroforestry has the potential to not only help farmers harness the interactions between the different components of an agroforestry system to their advantage but also shine light on fundamental interactions between soil, plants, trees, and livestock while offering a sustainable agricultural method beneficial to all agroforestry stakeholders.

KEYWORDS

data-driven agroforestry, agroforestry, precision agriculture, precision livestock farming, sensors, wireless sensor networks

1 Introduction

Agroforestry is a multi-functional land use system that can be basically described as agriculture with trees and livestock. Agroforestry systems take advantage of the mostly poorly understood interactions that occur amongst crops, trees and livestock. Agroforestry has been demonstrated to present numerous benefits which include



conservation of biodiversity¹, regulation of natural pests and diseases, regulation of soil, increased air and water quality, efficient cycling of nutrients, and resilience to climate change (Rao et al., 1997; Mateo-Sagasta et al., 2009; Smith et al., 2013; Khan et al., 2021). This form of land management is not a novel idea, and dates back to at least the middle ages in the developing world, and probably earlier in other cultures (Steppler and Nair, 1987).

John Bene from Canada’s International Development Research Centre was the first in the early 1970s to coin the term agroforestry and highlight the benefits of a multi-functional land use system². Further progress led to the establishment of the International Council for Research in Agroforestry (ICRAF) in 1978 to promote agroforestry research in developing countries (Steppler and Nair, 1987). Since then, agroforestry has attracted strong interest as evidenced by the compilation of articles shown in Figure 1 where the number of publications in the electronic database Scopus™ was obtained by using the keywords “agroforestry,” “precision agriculture,” and “agroforestry and sensors.” It is not surprising that the exponential increase in the number of research articles coincide with the birth of the ICRAF. Most of the research articles however focus on tropical climates and rely on a *a posteriori* measurements.

Figure 1 shows that the increase in precision agriculture research coincide with the rise of technological development, especially with the Internet of Things (IoT). Precision agriculture is defined as a management strategy that considers temporal and spatial variability to improve the sustainability of agricultural production³ (Mulla and Khosla, 2016). Similarly to precision agriculture, precision livestock farming (PLF) is becoming increasingly popular. Precision livestock farming refers to the management and monitoring of livestock through the use of real-time, continuous monitoring of animal health, welfare, production, reproduction, and environmental impact (Berckmans, 2017). As such, they both rely on the heavy use of sensors whose relevant sensing modalities will be reviewed in this paper. This type of management system based on a data-driven approach has the potential to meet the increasing demand for food while ensuring sustainable farming practices (Precision farming, 2018).

In contrast, few data-driven approach studies exist for agroforestry systems as shown in the remarkably small number of papers combining agroforestry and sensors, which might be due to the lack of knowledge in wireless sensor technology from the agroforestry community. Research in agroforestry could benefit from sensors and wireless sensor networks that are deployed today in typical monocropping

1 <https://www.worldagroforestry.org/about/agroforestry>

2 <https://www.worldagroforestry.org/about/history>

3 <https://www.ispag.org/about/definition>

agricultural systems. This paper attempts therefore to investigate the sensors used in precision agriculture and see how these could benefit agroforestry.

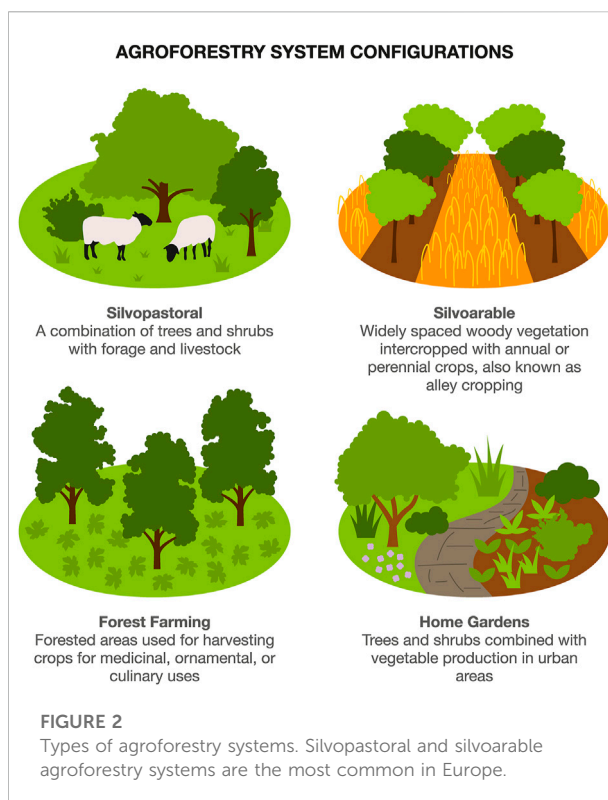
Section 2 presents a review of agroforestry in temperate climates and highlights the main gaps in current agroforestry research. A broad review of precision agriculture is provided in Section 3 with an emphasis on the type of sensors and the manner of which wireless sensor networks that are currently being used in agriculture. Section 4 presents an overview of precision livestock farming and the types of sensors used in livestock farming. Permaculture is presented in Section 5 and compared to precision farming and agroforestry. A new field of study, called data-driven agroforestry (DDA), is advocated for in Section 6 where the potential of combining the non-invasive nature of miniaturized sensors and their mode of interrogation with agroforestry methods. In addition, this section includes suggestions of sensors to be used to measure the interactions in an agroforestry system as well as areas that still need development.

2 Principles of agroforestry

As the world population increases, there is a growing need for multi-functional land use systems that can meet the multiple demands of food and fuel production, environmental and biodiversity protection, and has the capacity for adaptation and resilience to climate change (Hislop and Claridge, 2000; Smith et al., 2013). Agroforestry can be a sustainable alternative to traditional agricultural practices by reducing its negative impacts by, for example, regulating soil, water, and air quality (Hislop and Claridge, 2000; Smith et al., 2013; Augère-Granie, 2020).

Currently, agriculture accounts for 70% of water withdrawals worldwide and is one of the major contributors to water pollution, according to the Food and Agriculture Organization (FAO) (Mateo-Sagasta et al., 2009). Farms discharge large quantities of agrochemicals, organic matter, drug residues, sediments, and saline drainage into bodies of water (Mateo-Sagasta et al., 2009). In most high-income countries, this agricultural pollution has overtaken contamination from settlements and industries as the main factor in the degradation of inland and coastal waters (Mateo-Sagasta et al., 2009). This pollution causes eutrophication in aquatic ecosystems and human health disorders (Mateo-Sagasta et al., 2009).

Moreover, there is growing evidence that agroforestry systems increase overall productivity (Augère-Granie, 2020; Khan et al., 2021). In agroforestry systems, productivity can be measured using the Land Equivalent Ratio which compares the yield from growing two or more components together versus the yield from growing them separately (Augère-Granie, 2020). Moreover, agroforestry



systems do not need as much pesticide and fertilizer as traditional monocropping systems, thus reducing the cost of farming inputs (Perks et al., 2018; Augère-Granie, 2020). When livestock are introduced into the system, agroforestry can also reduce feeding costs (Perks et al., 2018). Apart from crops and livestock, agroforestry systems have the ability to produce outputs from the trees such as food, fuel, fodder, fibre, and timber which could yield an increase in economic profit due to the multiple outputs from this type of system (Augère-Granie, 2020). In addition, these multiple outputs reduce the risk associated with producing one product in the event of shortage periods due to adverse weather conditions or crop disease (Hislop and Claridge, 2000; Perks et al., 2018).

Agroforestry systems also benefit from increased animal welfare by providing protection from wind, rain, sun and the cold (Augère-Granie, 2020). Moreover, shrubs or trees offer protection from predators and encourages natural animal behaviour such as foraging (Augère-Granie, 2020). Lastly, agroforestry systems can also have recreational benefits (Hislop and Claridge, 2000; Augère-Granie, 2020). The motivation behind agroforestry is therefore multi-fold. Discovering the means to monitor, understand, and manage the interactions of the various agents within this ecosystem is the key to unlocking its full potential.

2.1 Types of agroforestry systems

There are several types of agroforestry systems used around the world. As shown in [Figure 2](#), common configurations include ([Mosquera-Losada et al., 2018](#)):

- Silvopastoral systems which consist of a combination of trees or shrubs with forage and livestock ([Mosquera-Losada et al., 2018](#)).
- Silvoarable systems which are widely spaced woody vegetation intercropped with annual or perennial crops, also known as alley cropping ([Mosquera-Losada et al., 2018](#)).
- Forest farming systems which are forested areas used for harvesting crops for medicinal, ornamental, or culinary uses ([Mosquera-Losada et al., 2018](#)).
- Homegardens which combine trees or shrubs with vegetable production in urban areas ([Mosquera-Losada et al., 2018](#)).

Silvopastoral and silvoarable systems tend to be more frequent in Scotland and the United Kingdom and thus will only be considered here. Within silvopastoral and silvoarable agroforestry systems, there are several options for combining trees and shrubs with crops or livestock such as ([Mosquera-Losada et al., 2018](#); [Perks et al., 2018](#)):

- Windbreaks and riparian buffer strips made of trees or shrubs to act as a shelterbelt.
- Rows of trees or shrubs ([Perks et al., 2018](#)).
- Single trees or tree cluster arrangements. These are best applied to silvopastoral systems ([Perks et al., 2018](#)).

Depending on the agroforestry practice used, the arrangement of components, and the types of trees, shrubs, and crops planted, there will be differing interactions that take place thus, each having potentially different outcomes.

2.2 Effects of interactions in agroforestry systems

The nature of interactions taking place in agroforestry systems arise from the addition of trees or shrubs to arable or livestock systems. These interactions affect the following areas ([Rao et al., 1997](#); [Smith et al., 2013](#)):

- Soil fertility including soil chemical, physical and biological interactions.
- Competition for soil water, nutrients, and sunlight.
- Microclimate
- Pests and diseases
- Soil conservation

These will be further explained in the next sections.

2.2.1 Soil fertility

Sustainable agriculture is highly dependent on a large community of soil organisms interacting with diverse crops to recycle nutrients ([Østergård et al., 2009](#)). The most important determinants of soil quality and health are the amount of soil organic matter and the level of microbial diversity ([Østergård et al., 2009](#)). These improve soil structure and water retention making soil more tolerant to stresses like droughts and compaction. They also help sequester carbon and mitigate the effects of soil salinity, acidity and alkalinity ([Østergård et al., 2009](#)).

Improved physical soil properties include better soil aggregation, lower bulk density, lower resistance to water penetration, and improved soil porosity ([Rao et al., 1997](#)). This results in improved water infiltration, higher saturated hydraulic conductivity, and higher water holding capacity ([Rao et al., 1997](#)). These properties originate primarily from increased soil organic matter and root activity ([Rao et al., 1997](#)). For instance, the decay of roots leaving behind channels increases infiltrability and enhances groundwater recharge ([Bargués Tobella et al., 2014](#); [Bayala and Prieto, 2020](#)). Through the process of hydraulic lift, trees or shrubs with deep roots can lift and redistribute water and nutrients, inaccessible to crops to the upper layers of the soil thus acting as bio-irrigators to adjacent plants ([Bayala and Prieto, 2020](#)). During the dry season, trees obtain most of their water from deep soil levels when upper soil levels are dry and can distribute this water to the upper levels for the crops to access ([Bayala and Prieto, 2020](#)). This can help increase survival and growth of crops by providing a buffer against droughts and ensure productivity in regions with erratic rainfall ([Bayala and Prieto, 2020](#)).

Furthermore, because of the access of the tree to nutrients in deeper soil layers, once leaves fall onto the soil and decompose, increasing soil organic matter, these nutrients get cycled into the upper soil layers making them accessible to crops in this way as well ([Rao et al., 1997](#); [Bayala and Prieto, 2020](#)). This promotes microbial processes and decomposition which release nutrients from organic matter and soil minerals ([Rao et al., 1997](#); [Bayala and Prieto, 2020](#)).

Common mycorrhizal networks (CMN) also play a role in linking plants together ([Alaux et al., 2021](#)). These are formed by mycorrhizal fungi which make up a complex and dense network of mycelium in soil allowing the plant's roots to access otherwise inaccessible soil. This network allows for an exchange of nutrients and water affecting plant resistance and tolerance to stresses ([Alaux et al., 2021](#)). There is evidence that sustainable agricultural practices, such as agroforestry, have a positive effect on CMNs ([Battie-Laclau et al., 2020](#); [Alaux et al., 2021](#)).

2.2.2 Competitive landscape

Competition for resources including water, nutrients, and light occurs between the different components of an agroforestry system ([Rao et al., 1997](#)).

Root distribution from many trees overlaps the upper soil layers with shallower root systems from the crops which could generate competition for water and nutrients (Bayala and Prieto, 2020). This can be mitigated with methods such as tree pruning which has proven to reduce roots in the upper soil levels (Bayala and Prieto, 2020).

Another form of competition stems from the shade from the trees that can limit the amount of light received by crops under the canopy, but also protect livestock from sun overexposure as explained in the next section (Hislop and Claridge, 2000). However, protection from the trees can extend the grass growth season and increase the soil temperature in early spring and late autumn (The Woodland Trust, 2017).

2.2.3 Microclimate

Another result from planting trees or shrubs is their effect on the creation of a microclimate through the alteration of temperature, humidity and wind speed (Hislop and Claridge, 2000). In urban areas, tree planting can result in temperature change by several degrees (Vaz Monteiro et al., 2019). Within agriculture, trees can improve animal welfare by providing shelter for outdoor livestock from rain, wind, and sun (Perks et al., 2018). Moreover, the lowered wind speeds can reduce significant problems with wind erosion of soils (Perks et al., 2018). In addition, the tree's canopy offers protection from raindrop impact reducing the formation of soil crusts which limits water infiltration (Bargués Tobella et al., 2014).

Heat increase is expected in the future which will affect animal pregnancy rates, weight, milk production, and overall animal health (Smith et al., 2022). The shade provided by trees, specifically in silvopastoral systems, can ease some of the issues that will be encountered in the future (Smith et al., 2022).

2.3 Agroforestry systems in temperate climates

Most of the research studies published in agroforestry have focused on tropical climates probably due to the higher popularity of agroforestry systems in tropical climates. This review article concentrates on temperate systems, more specifically silvopastoral systems (Bergez et al., 1997; Teklehaimanot et al., 2002; Morgan-Davies et al., 2008; The Woodland Trust, 2014; The Woodland Trust, 2015; Beckert et al., 2016; Lunka and Patil, 2016; Upson et al., 2016; The Woodland Trust, 2017; McAdam, 2018; Pantera et al., 2018; Smith, 2018; Lehmann et al., 2020; Varah et al., 2020) and silvoarable systems (Pantera et al., 2018; Smith, 2018; Lehmann et al., 2020; Varah et al., 2020).

For such studies, the age of the agroforestry systems needs to be considered as the time it takes for farm production from trees is a lot greater than that of annual crops and livestock (Raskin and Osburn, 2019). The amount of time required depends on the

tree species and the end use of the tree product (Raskin and Osburn, 2019). The economics of agroforestry are further discussed in (Hislop and Claridge, 2000) and (Raskin and Osburn, 2019). Table 1 presents a breakdown of the location and age of the agroforestry systems reviewed.

Articles consulted in this review have been separated according to objectives of agroforestry systems including increase of productivity (Morgan-Davies et al., 2008; The Woodland Trust, 2014; The Woodland Trust, 2015; The Woodland Trust, 2017; Pantera et al., 2018); Teklehaimanot et al., 2002; Lehmann et al., 2020) and environmental benefits (Bergez et al., 1997; The Woodland Trust, 2014; The Woodland Trust, 2015; Beckert et al., 2016; Lunka and Patil, 2016; Upson et al., 2016; McAdam, 2018; Pantera et al., 2018; Varah et al., 2020), and also as to whether the interactions described were studied from a scientific or technological point of view (Bergez et al., 1997; Smith, 2018). The management of the agroforestry system will differ depending on the pursued objectives of the agroforestry plot. The following sub-sections discuss and group the most relevant papers by objective and summarize the performance metrics used to measure and quantify this objective.

2.3.1 Productivity

The productivity objective considers the increased economic profit that can be harvested from the agroforestry system. This includes crop, tree, and livestock yield (direct performance metrics) as well as the decrease of livestock mortality and overall livestock welfare (indirect performance metrics). A review of all performance metrics and key performance indicators related to this objective is provided in Table 2.

Morgan-Davies et al. combined hill sheep production with native woodland creation in a Scottish mountain valley and compared initial bio-economical modelling results and data over a 5-year period of study (Morgan-Davies et al., 2008). Some of the defined performance metrics are indicated in Table 2. Results demonstrate that, with the exception of the expected slow rate of woodland establishment, results exceeded expectation according to the combined system economics where actual returns were 20% more than predicted (Morgan-Davies et al., 2008).

In (Pantera et al., 2018), Pentarra et al. reviewed different European agroforestry systems to understand how the integration of understory crops such as chickpeas and barley, and/or livestock within high value tree systems like apple orchards and olive groves can affect production, environmental, or economic aspects. Their review illustrates that this land management system provides financial benefits from the extra products provided and reduces required management, societal benefits from the aesthetics of the landscape, and environmental benefits including improved carbon sequestration for climate regulation and reduced water pollution (Pantera et al., 2018).

TABLE 1 Review of locations of agroforestry system.

Location	Age		
	0–10 years	> 10 years	Not indicated
United Kingdom	(Varah et al., 2020; Morgan-Davies et al., 2008; The Woodland Trust, (2017); Bergez et al., 1997; Smith, (2018); Teklehaimanot et al. (2002)	(Beckert et al., 2016; Lunka and Patil, 2016; Upson et al., 2016; McAdam, 2018; Lehmann et al., 2020; Varah et al., 2020)	Pantera et al. (2018) The Woodland Trust, (2015); The Woodland Trust, (2017)
France, Spain, Greece			Pantera et al. (2018)
Italy, Romania, Denmark, Poland		Lehmann et al. (2020)	Pantera et al. (2018)

TABLE 2 Productivity measurements.

Performance metrics	Key performance indicators
Productivity	Number of lambs born (Morgan-Davies et al., 2008) Birth weight (Morgan-Davies et al., 2008) Weaning weight (Morgan-Davies et al., 2008) Mortality (Morgan-Davies et al., 2008)
Economic measure	Number of lambs and ewes sold (Morgan-Davies et al., 2008) Prices of animals (Morgan-Davies et al., 2008) Costs of off-wintering management (Morgan-Davies et al., 2008) Costs and income related to field (Morgan-Davies et al., 2008) Land Equivalent Ratio for agronomic productivity (Lehmann et al., 2020)
Tree measurements	Tree numbers (Morgan-Davies et al., 2008) Tree height (Teklehaimanot et al., 2002; Morgan-Davies et al., 2008) Tree diameter (Teklehaimanot et al., 2002) Signs of browsing (Morgan-Davies et al., 2008) Stem damage (Morgan-Davies et al., 2008)
Vegetation measure	Sward structure and species composition (Morgan-Davies et al., 2008) Biomass and productivity (Morgan-Davies et al., 2008) Growing season (The Woodland Trust, 2017) Pasture Production (The Woodland Trust, 2015)
Biodiversity indicators	Bird surveys (Morgan-Davies et al., 2008) Earthworm count (The Woodland Trust, 2017)

The case study in (The Woodland Trust, 2017) demonstrated how mob grazing, tree and hedge planting can improve farm productivity and soil health while decreasing input costs. A decrease in lamb mortality was witnessed due to the new availability of shelter, higher biodiversity in the soil measured by worm counting, and a longer grass growing season (The

Woodland Trust, 2017). Similarly in (The Woodland Trust, 2014), the planting of trees and shrubs helped reduce lamb mortality due to hypothermia. Trees also have the effect of reducing water pollution and poaching (The Woodland Trust, 2014). In addition, the case study in (The Woodland Trust, 2015) showed how the planting of trees improved soil conditions,

TABLE 3 Key performance indicators for environmental benefits.

	Measurand	Measurement method
Biodiversity indicators	Pollinator abundance	Transect Walking (Varah et al., 2020)
	Species richness	Pan traps (Varah et al., 2020)
	Pollination service	Phytometers (Varah et al., 2020)
Soil indicators	Soil organic carbon	Laboratory (Beckert et al., 2016; Upson et al., 2016; McAdam, 2018)
	Soil moisture	Capacitance soil moisture sensor (Upson et al., 2016) Unspecified (McAdam, 2018)
	Infiltration potential	Penetrologger (McAdam, 2018)
	Soil water infiltration	Single ring infiltrometer (Lunka and Patil, 2016)
	Soil bulk density	Laboratory (Lunka and Patil, 2016; Upson et al., 2016)
	Fine root mass	Laboratory (Upson et al., 2016)
	Tree measurements	Tree carbon content
Canopy interception		Canopy interception gauges (Lunka and Patil, 2016)
PAR		PAR DRP-1 sensor (Bergez et al., 1997)
Leaf area development		Linear interpolation (Bergez et al., 1997)
Productivity	Pasture production	Carrying capacity (Bergez et al., 1997)

provided shelter to dairy cows as well as nutritional and medicinal fodder to the herd.

Teklehaimanot *et al.* compared the growth of trees evenly dispersed in the plot against those planted in clumps in a silvopastoral system (Teklehaimanot *et al.*, 2002). Livestock productivity was measured to be the same regardless of the planting pattern or species (Teklehaimanot *et al.*, 2002). In addition, the growth of sycamore trees was found to be lower if highly spaced rather than in conventional forestry, while planting trees in small clumps reduced tree protection costs (Teklehaimanot *et al.*, 2002).

Lehmann *et al.* assessed in (Lehmann *et al.*, 2020) the agronomic productivity and economic viability of diverse agroforestry systems in Europe. Five agroforestry systems were reviewed and the Land Equivalent Ratio was calculated providing evidence for agronomic productivity and economic viability of agroforestry systems (Lehmann *et al.*, 2020).

2.3.2 Environmental benefits

Environmental benefits include biodiversity, soil health, and water quality as shown in Table 3. Key performance indicators include biodiversity and soil indicators, tree measurements and productivity.

Varah *et al.* (2020) studied whether agroforestry can benefit wild pollinators. The study looked at wild insect pollinator abundance, species richness, and pollination services in six organic agroforestry and monocrop systems in the United Kingdom. They measured pollinator abundance by

transect walking, species richness with pan traps, and pollination services with phytometers. Agroforestry systems in the United Kingdom were judged to be able to play a part in sustainable agriculture by supporting a greater number of wild insect pollinators, greater pollination service and in some sites greater wild bee species (Varah *et al.*, 2020).

Beckert *et al.* compared the carbon sequestration potential of silvopastoral and woodland plots by taking soil samples, treating them in a laboratory, and calculating the amount of soil organic carbon (Beckert *et al.*, 2016). They showed that silvopasture had similar or even greater soil carbon stocks compared to woodland plots (Beckert *et al.*, 2016).

Canopy interception, soil water infiltration, and bulk density were compared in (Lunka and Patil, 2016) between a control pasture and two silvopastoral planting configurations composed of trees planted evenly and grazed, and trees clumped in fenced-off ungrazed plots, to characterize the potential of these configurations to reduce local flood risk. Soil water infiltration was measured using a single ring infiltrometer; bulk density was determined by extracting a soil sample and analysing it in a laboratory. Canopy interception measurements were made using throughfall gauges. The results suggest that silvopastoral systems are more likely to benefit from clumped and ungrazed tree configurations because of enhanced infiltration, lower soil compaction, and increased canopy interception (Lunka and Patil, 2016).

To the best of the authors' knowledge and at the time of writing, references (Bergez *et al.*, 1997; McAdam, 2018) and

(Upson et al., 2016) are the only ones that specifically mention the use of in-field sensing. In (McAdam, 2018), MacAdam demonstrates that silvopastoral systems can significantly extend the grazing season to improve grass utilisation. They measured soil carbon storage by sampling and analysing the soil. Total tree carbon content was measured by excavating the tree and analysing it. Soil resistance to penetration, which gives an indication of water infiltration potential, was measured weekly using a penetrometer, an instrument allowing *in situ* measurement of soil penetration. Soil moisture was also measured weekly. The method of measurement is however not specified. In (Bergez et al., 1997), photosynthetically active radiation (PAR) was measured using a PAR quantum DRP-1 sensor to determine how widely spaced eight-year-old trees in a silvopastoral system affect light reaching the sward and how the light is modified depending on the tree planting density, weather, and development of foliage area of the trees. Other measurements included overall pasture production measured by the carrying capacity which is dependent on the weight and number of animals. The result recorded a small amount of radiation intercepted by the tree canopies which led to no significant differences observed in the annual carrying capacity (Bergez et al., 1997). The study in (Upson et al., 2016) determined the effect of woodland and silvopastoral systems on soil bulk density and organic carbon content. The authors measured bulk density, fine root mass, and soil organic carbon in the laboratory, and used an *in situ* capacitive soil moisture sensor (Upson et al., 2016). They showed that, 14 years after planting, the silvopastoral agroforestry system stored about 5% more carbon than the equivalent areas of separate woodland and pasture (Upson et al., 2016).

2.3.3 Interactions studies

Only two papers in the review had the objective of understanding interactions of the components of an agroforestry system (Bergez et al., 1997; Smith, 2018). In (Smith, 2018) the authors reported on the interactions between trees, crops, and both wild animals and livestock by measuring factors such as tree and animal interactions (number of trees browsed by livestock), pasture production, and earthworm abundance. They found that, in the first 6 years, there was no significant impact of trees on alley crops. The protection of the trees from livestock damage was however essential in the early years.

2.4 Discussion

Despite the substantial amount of research in agroforestry, only three papers used any type of *in situ* soil measurements (Bergez et al., 1997; Upson et al., 2016; McAdam, 2018). Most of the papers used destructive, remote, or expensive methods of measurement. No papers reported the use of data-driven

approaches to studying these temporal and spatial interactions in real-time. A large area of research is still yet to be investigated.

3 Precision agriculture

Precision agriculture (PA) is defined as a management strategy that takes account of the temporal and spatial variability to support management decisions for improved resource efficiency, productivity, quality, profitability, and sustainability of agricultural production⁴. The main goal of PA is to apply just enough resources to sustain or increase productivity (Zarco-Tejada et al., 2014). Precision agriculture benefits the environment by this reduced use of farming inputs to avoid serious negative environmental effects (Bongiovanni and Lowenberg-DeBoer, 2004; Mateo-Sagasta et al., 2009). The rapid technological advancements in sensors, big data analytics, and cloud computing have increased the use and interest in precision agriculture.

A key technology enabling PA is Wireless Sensor Networks (WSN). These are reviewed first in this section, followed by communication protocols. Lastly, sensors used in precision agriculture are presented and grouped into three categories: soil, environmental, and plant. Their working principles are then explained.

3.1 Wireless sensor networks

A Wireless Sensor Network is a network of wireless sensors, called nodes, which communicate data wirelessly to a base station or coordinator node (Jawad et al., 2017). WSNs can be used in agriculture to collect, monitor, and analyse data from the field (Kumar and Ilango, 2018). In agricultural settings, WSNs should monitor *in situ* a large area with precise field information, helping minimize the burden of farmers in terms of efforts and manpower needed to retrieve the necessary information (Haule and Michael, 2014; Kumar and Ilango, 2018).

WSNs can suffer from short communication range, low energy efficiency, poor communication bandwidth, and poor fault tolerance (Jawad et al., 2017). It is likely that communication bandwidth is unlikely to be an issue as the amount of information requested, although in real-time, does not need to be collected at a high bit rate. Topography and presence of obstacles in agricultural fields could result in a loss or weakening of signals (Jawad et al., 2017). Sensor nodes are mainly limited by their battery, thus energy efficiency or energy harvesting are imperative to prolong battery life, potential solutions of which are provided in (Jawad et al., 2017). Lastly,

⁴ <https://www.ispag.org/about/definition>

TABLE 4 Summary of WSN communication technology (Jawad et al., 2017; Mekki et al., 2019; Tang et al., 2021).

	ZigBee	Bluetooth	BLE	Wi-Fi	GPRS	LoRa	SigFox	NB-IoT	5G
Range	100 m	10–50 m	10 m	100 m	1–10 km	5–20 km	10–40 km	1–10 km	200 m
Bandwidth	2 MHz	1 MHz	1 MHz	22 MHz	200 kHz	< 500 kHz	< 100 Hz	200kHz	400 MHz
Data rate	20, 40, 250 kbps	1–3 Mbps	1 Mbps	11–54 and 150 Mbps	≤ 170 kbps	50 kbps	100 bps	200 kbps	1 Gbps
Cost	Low	Low	Low	High	Medium	Low	Low	Medium	Low

TABLE 5 Estimated minimum data rates for agricultural measurements.

Measurements	Minimum data rates
Soil	2 per week
Environment	1 per hour
Plant	1 per day

sensor nodes are fault prone due to issues such as battery depletion and hardware fault (Ojha et al., 2015).

3.1.1 Wireless communication protocols

Some of the different wireless protocols and standards used in agriculture include ZigBee, Bluetooth, Wi-Fi, GPRS/2G/3G, Long Range Radio (LoRa), and SigFox. Table 4 compares these along with the Narrowband IoT (NB-IoT) and 5G, although they are not yet widely used in agriculture.

The ZigBee protocol is characterised by its low cost and low power consumption due to its low duty cycle and sleep mode (Jawad et al., 2017). However, communication range is short so may not be suitable for all uses (Jawad et al., 2017). Bluetooth is widely available, easy to use, and has low power consumption with Bluetooth Low Energy (BLE) (Jawad et al., 2017). However, it has a short communication range that could make it impractical for some agricultural purposes (Jawad et al., 2017). Wi-Fi technology adopts data redundancy techniques but requires a high amount of power, long communication time, and a large data payload (Jawad et al., 2017). Throughput and delay are variable in GPRS technology (Ojha et al., 2015). Its performance also depends on the volume of consumers that share communication channels and resources (Ojha et al., 2015). LoRa is characterised by its low power consumption, and long communication range making it suitable for agricultural domains (Jawad et al., 2017; Gresl et al., 2021). However, LoRa gateways have a limited message capacity (Jawad et al., 2017). It is also complex and needs substantial hardware implementation (Jawad et al., 2017). SigFox has low power consumption and long range, however it has low data rates and slow transmission (Jawad et al.,

TABLE 6 Summary of measurands used in precision agriculture.

	Measurands
Soil Measurements	Soil Moisture Soil Temperature Soil Nutrients Soil pH Soil Texture Soil Salinity
Environmental Measurements	Atmospheric Pressure Temperature Humidity Light Intensity Wind Speed Wind Direction CO ₂
Plant Phenotypes	Growth Function Leaf Angle Chlorophyll Concentration

2017). Narrowband-IoT, along with SigFox and LoRa, are part of the low power wide area networks (LPWAN) (Mekki et al., 2019). However unlike SigFox and LoRa, NB-IoT deployment is limited to LTE base stations (Mekki et al., 2019). Most farms, especially in rural areas, may not have LTE coverage thus this option may be unsuitable for agricultural purposes (Mekki et al., 2019). The 5G network is characterised by its high speed and low latency (Tang et al., 2021). However, 5G uses a low frequency band and therefore a short range but achieves high connectivity through the use of small base stations (Tang et al., 2021). The application of 5G can be suitable to farming due to its wide coverage, low energy consumption, and low cost devices (Tang et al., 2021).

Due to its low power consumption and long communication range, currently LoRa is possibly today the best option for agricultural settings. In general, most agricultural measurements do not need a high data rate as the

TABLE 7 Soil measurement sensors.

Soil Moisture	EC-5	(Pascual et al., 2019)
	WATERMARK	(Fahmi et al., 2017)
	SEN0193	(Grimblatt et al., 2019)
	FC-28	(Abagissa et al., 2018)
	10HS	(Dursun and Ozden, 2011)
	SEN13322	(Kiani and Seyyedabbasi, 2018)
	Unspecified	(Haule and Michael, 2014; Sahitya et al., 2017; Keswani et al., 2019; Rathinam et al., 2019; Sanjeevi et al., 2020)
Soil Temperature	DS18B20	(Grimblatt et al., 2019)
	Unspecified	(Abagissa et al., 2018; Kiani and Seyyedabbasi, 2018; Keswani et al., 2019)
Soil Nutrients	ISL29125	(Grimblatt et al., 2019)
Soil pH	Unspecified	(Grimblatt et al., 2019)
Soil Texture	In laboratory	(Grimblatt et al., 2019)

measurements do not change with a high frequency. Due to the relatively low data rates, the sensors only use a small amount of power thus, a small solar panel would likely be sufficient to power the sensor. Table 5 suggests estimates for minimum data rates needed for soil, environmental, and plant measurements.

3.2 Remote sensing in precision agriculture

The high availability of satellites and unmanned aerial vehicles (UAV) and their high spatial, temporal, and spectral resolution have made remote sensing technologies more popular in agricultural settings (Sishodia et al., 2020). Remote sensing techniques can help detect pests and diseases, measure production⁵, crop stress, crop nutrient status, and soil moisture, just to name a few (Messina and Modica, 2020; Sishodia et al., 2020).

3.3 Measurands and sensors in precision agriculture

Quantification of soil quality, environmental conditions, and effects on plant phenotypes will depend on the measurands to monitor, the sensing modalities to use, and the type of sensor to perform the measurement. Table 6 summarises the types of measurands used in that regard. The following sections provide a breakdown of the different types of measurements and an overview of the sensors used to quantify the measurands.

⁵ <https://www.fao.org/soils-portal/about/en/>

3.3.1 Soil measurements

Soil has multiple important uses: it helps filter water, decompose materials, and mitigates the effects of climate change by acting as a sink for greenhouse gases. There are several aspects of soil that need to be taken into consideration in order to assess soil quality, understand the effects of farm management, and interpret the interactions that take place from different components on the soil.

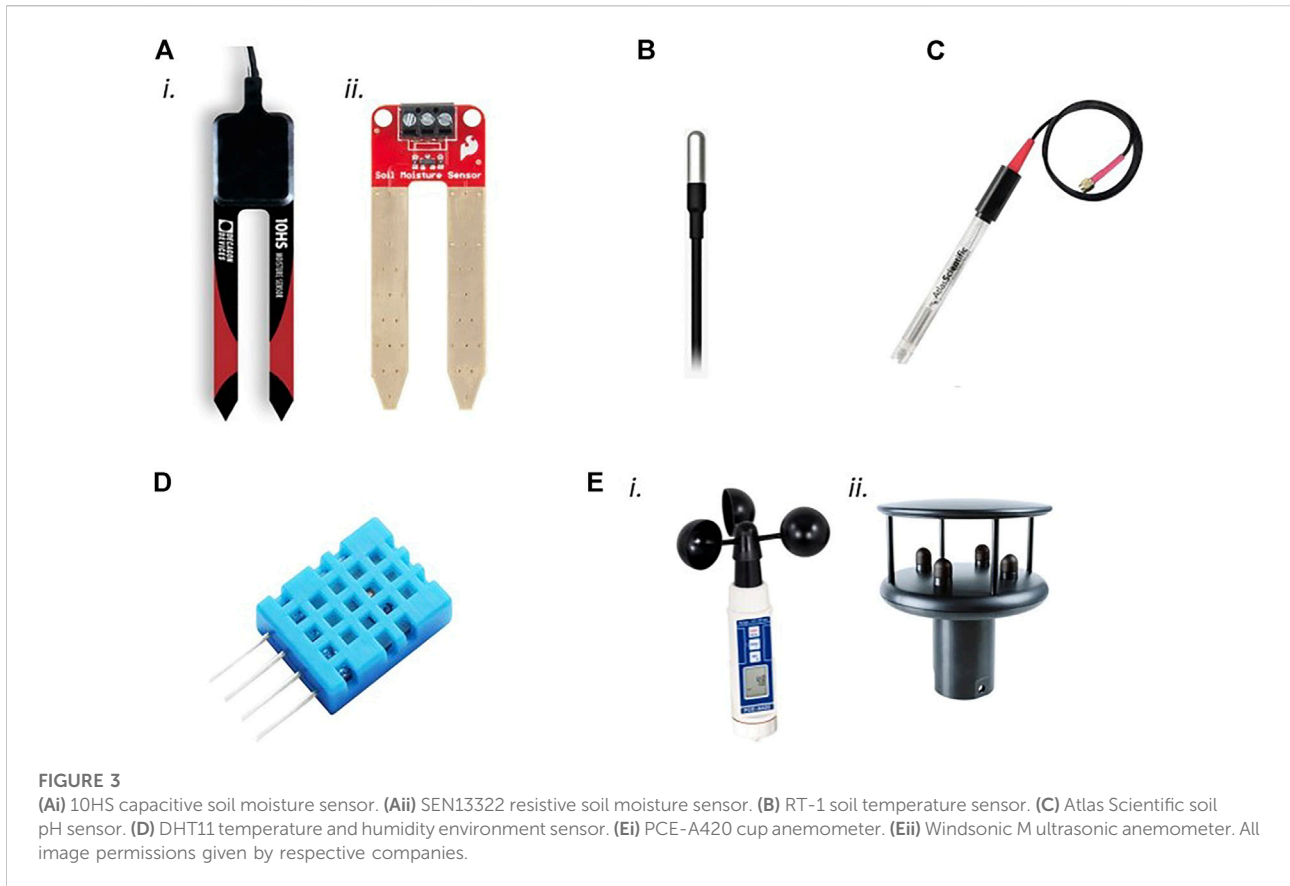
3.3.1.1 Soil moisture

Effective water usage is of high importance in agriculture (Barapatre and Patel, 2019). Soil moisture is a significant factor in determining yield; thus, soil moisture sensors can help farmers use water with efficacy and efficiency (Barapatre and Patel, 2019). Monitoring soil moisture provides important information on soil health and moisture retention which are key indicators of sustainable agroecosystems (Kashyap and Kumar, 2021). Soil moisture is the most sensed indicator as shown in Table 7, with 61% of papers reviewed quantifying this measurand.

Resistive and capacitive sensors are the two main types of sensors used for soil moisture. Resistive sensors such as FC-28⁶ and SEN13322⁷ use two probes to send a current through the soil and measure the resistance to quantify the moisture (Barapatre and Patel, 2019). Dry soil is a poor conductor, thus the less moisture, the more resistive the soil (Barapatre and Patel, 2019). However, resistive sensors are limited because of corrosion of the probes that could cause inaccurate measurements (Barapatre and Patel, 2019). In addition, adding fertilizer could decrease the soil resistance even if no water is added (Barapatre and Patel, 2019).

⁶ <https://naylampmechatronics.com/sensores-temperatura-y-humedad/47-sensor-de-humedad-de-suelo-fc-28.html>

⁷ <https://www.sparkfun.com/products/13322>



Another resistive soil moisture sensor is the WATERMARK granular matrix sensor⁸. It uses gypsum wafers surrounded by a porous granular filler material with electrodes embedded within it which is buried in the soil (Kashyap and Kumar, 2021). Gypsum begins to dissolve from the soil moisture which allows for ions to move within the porous material reducing the resistance between electrodes (Kashyap and Kumar, 2021). These sensors are easy to manufacture and low price, however they have poor accuracy, with errors ranging between 10% and 25%. In addition, the gypsum is affected by temperature and has a slow response to soil changes, about 24 h (Enciso et al., 2007; Kashyap and Kumar, 2021).

Capacitive sensors such as the EC-5⁹, SEN0193¹⁰, and 10HS¹¹, measure the dielectric permittivity constant of the soil (Barapatre and Patel, 2019). Such sensors are made out of a corrosion resistant material making them less susceptible to

corrosion than resistive soil moisture sensors (Barapatre and Patel, 2019). They are also more specific as inputs such as fertilizers will not significantly alter their readings (Barapatre and Patel, 2019). These types of sensors operate at a frequency in the order of 10 MHz (Kashyap and Kumar, 2021). Both the EC-5 and 10HS operate at a frequency of 70 MHz which minimizes the salinity and textural effects of the soil. In addition, the 10HS has longer probes compared to EC-5 and SEN0193 thus allowing for measurement of up to 1 L of soil volume compared to 0.2 L for EC-5. This makes the 10HS better at averaging varying soil moisture and characterizing spatial variability. Figure 3A shows examples of these sensors.

3.3.1.2 Soil temperature

Soil temperature influences all processes that occur in the soil including water content, acquisition of mineral nutrients, and storage of organic carbon (Pregitzer and King, 2005). In addition, soil temperature affects plant physiological aspects like root growth and composition, and function of soil microbial communities (Pregitzer and King, 2005). There are several factors that affect soil temperature such as atmospheric properties, surface properties like land cover and topography, and soil properties such as porosity and bulk density (Lehnert, 2014).

⁸ <https://irrometer.com/sensors.html>

⁹ <https://www.metergroup.com/environment/products/ec-5-soil-moisture-sensor/>

¹⁰ https://wiki.dfrobot.com/Capacitive_Soil_Moisture_Sensor_SKU_SEN0193

¹¹ <http://www.labcell.com/media/24207/10hs-manual.pdf>

The DS18B20 is a digital thermometer that operates without an external power supply¹². Power can be supplied through the control line which charges an internal capacitor supplying power to the device when the bus is low. The sensor measures temperatures ranging from -55°C to 125°C with a user-configurable resolution of 0.5°C , 0.25°C , 0.125°C , or 0.0625°C . The DS18B20 has an accuracy of $\pm 0.5^{\circ}\text{C}$ from -10°C to 85°C .

Figure 3B shows an examples of the RT-1¹³ soil temperature sensor.

3.3.1.3 Soil nutrients, pH and texture

Nitrogen (N), phosphorous (P), and potassium (K) are considered the most important macronutrients as they are responsible for assimilating proteins, synthesizing metabolic energy, and producing ATP (Burton et al., 2020). These nutrients vary spatially across the agricultural field. Limited nutrients can result in a reduction of plant growth and a change in plant structure (Burton et al., 2020). Excess of nutrients which are not absorbed, are leached into ground and surface water during rainfall and irrigation which can pollute local water supplies harming humans and biodiversity (Burton et al., 2020).

In situ soil nutrient sensing currently remains a technical challenge (Burton et al., 2020). Most soil nutrient measurements involve random grid sampling to obtain soil cores. The cores are transported to a laboratory where the cores are analysed using methods such as Kjeldahl wet digestion, dumas combustion, and gas chromatography mass spectrometry (Muñoz-Huerta et al., 2013; Burton et al., 2020). Although these methods are highly accurate, they are expensive, time-consuming, and do not allow for real-time *in situ* sensing (Burton et al., 2020).

Overall, *in situ* soil nutrient sensors involve optical, or electrochemical methods (Burton et al., 2020). Optical sensors identify soil nutrients based on the magnitude of energy absorbed and reflected by nutrient ions (Burton et al., 2020). Electrochemical sensors use ion-selective electrodes to initiate a current or voltage output that reflects the concentration of target ions (Burton et al., 2020).

Very few articles reviewed measure soil nutrients. One of them uses the ISL29125 light sensor to measure the reflection characteristics of the N, P, and K minerals found in soil (Grimblatt et al., 2019). The measurement is done through the reflection characteristics of these minerals based on the Lambert-Beers Law. At the time of writing, the described system was not tested, thus there are no results as to how accurate this method of measurement is.

In (Golicz et al., 2019) authors investigate the potential for a smartphone to assess soil nutrients through the use of

commercially available, single use, nitrate and phosphate sensitive test strips. The smartphone application can relate the reaction colour of the strips to the concentration of soil nutrients. They concluded that smartphone-mediated soil analysis can be successful for nitrate-nitrogen, $\text{NO}_3^- - \text{N}$, but has limited success for assessment of soil phosphate, $\text{PO}_4^{3-} - \text{P}$, content. Similarly, in (Burton et al., 2018) the use of disposable IoT gardening soil sheets are explored. The inkjet-printed sheets are capable of analyzing real-time soil nitrate concentration using a nitrate doped polypyrrole ion selective electrode sensor array. The real-time data measurements are transmitted *via* Waspote, ZigBee, a cloud server, and a mobile device.

In (Smolka et al., 2017) the researchers developed a mobile lab-on-a-chip device to measure soil nutrients including NO_3^- , NH_4^+ , K, and PO_4 . The sensor uses capillary electrophoresis to separate different ions and pass them through a detector. Although the time to get the measurements was high, the sensors successfully detect soil nutrients.

Reference (Pei et al., 2019) demonstrates the potential for *in situ* estimation of soil profile properties. They use optical diffuse reflectance spectroscopy to measure soil properties in the field such as soil organic carbon, total nitrogen, moisture, soil texture, cation exchange capacity, calcium, magnesium, potassium, and pH (Pei et al., 2019).

There are further developments using handheld, portable X-ray fluorescence spectrometers and near infrared spectrometers which claim to be able to detect soil organic matter (SOM) and soil organic carbon (SOC). The authors of (Ravansari et al., 2021), which created¹⁴, developed an attachment for a portable x-ray fluorescence (PXRF) spectrometer, which cannot directly measure carbon or other light elements, using visible near infrared (Vis-NIR). This attachment captures antecedent x-rays from the PXRF and has initially proven to estimate soil nutrients. The S1 Titan developed by Bruker¹⁵, is a PXRF spectrometer. It can detect elements from magnesium to uranium at low concentrations, however as just mentioned, it cannot quantify light elements such as carbon. Thus, this does not give complete information on SOM or SOC.

Soil pH affects nutrient solubility and availability (McCauley et al., 2009). Factors that influence soil pH include organic matter decomposition, NH_4^+ fertilizers, climate, and land management practices (McCauley et al., 2009). The Atlas Scientific pH probe is an example of a commercial pH soil sensor¹⁶ and can be seen in Figure 3C. It has a glass membrane which allows hydrogen ions from the soil to diffuse to the outer layers of the probe. The difference in concentrations of the ions between the probe and

12 <https://datasheets.maximintegrated.com/en/ds/DS18B20.pdf>

13 <https://www.metergroup.com/en/meter-environment/products/rt-1-soil-temperature-sensor>

14 <https://www.xcentric.tech/>

15 <https://www.bruker.com/en/products-and-solutions/elemental-analyzers/handheld-xrf-spectrometers/S1-TITAN.html>

16 <https://atlas-scientific.com/probes/consumer-grade-ph-probe/>

TABLE 8 Environmental measurement sensors.

Temperature	Si7021 (Grimblatt et al., 2019) DHT11 (Haule and Michael, 2014; Sahitya et al., 2017; Sanjeevi et al., 2020) DHT22 (Cabaccan et al., 2017) Unspecified (Fahmi et al., 2017; Zhang et al., 2017; Abagissa et al., 2018; Foughali et al., 2018; Kiani and Seyyedabbasi, 2018; Keswani et al., 2019; Rathinam et al., 2019)
Humidity	DHT11 (Haule and Michael, 2014; Sahitya et al., 2017; Sanjeevi et al., 2020) DHT22 (Cabaccan et al., 2017) C10-M53R (Zhang et al., 2017) Unspecified (Fahmi et al., 2017; Abagissa et al., 2018; Foughali et al., 2018; Kiani and Seyyedabbasi, 2018; Keswani et al., 2019; Rathinam et al., 2019)
Atmospheric Pressure	MPX4115A (Fahmi et al., 2017) BMP180 (Sanjeevi et al., 2020)
Light Intensity	BH1750FVI (Zhang et al., 2017) Unspecified (Cabaccan et al., 2017; Sahitya et al., 2017; Abagissa et al., 2018; Keswani et al., 2019)
Rain	Control module made by authors (Patokar and Gohokar, 2018)
Bio sensor	Unspecified (Rathinam et al., 2019)
Wind Speed	Unspecified (Abagissa et al., 2018)

the soil will give a small current which corresponds to the pH. It needs to be calibrated about every 6 months. The Atlas Scientific pH probe measures pH in the range of 2–3 with an accuracy and resolution of $\pm 0.1^\circ$ in the temperature range of 1°C – 60°C .

Soil texture refers to the size distribution of soil particles (Dexter, 2004). Textures affect water and nutrient retention (Dexter, 2004; Grimblatt et al., 2019). Soil texture does not change frequently, thus such measurements are usually carried out once in a laboratory.

3.3.2 Environmental measurements

Environmental measures including air temperature, humidity, pressure, light intensity, and wind speed have significant effects on the health and productivity of crops and trees (Ferrante and Mariani, 2018). Temperature affects a plants metabolism as temperatures either too high or too low can compromise plant growth and damage crops (Ferrante and Mariani, 2018). Light allows the plant to convert water and carbon dioxide into carbohydrates through the process of photosynthesis. The correct light intensity is necessary to drive production, however too much or too little can affect humidity, crop transpiration, and water balance (Ferrante and Mariani, 2018). Overall, these external environmental measures could cause abiotic stress and result in a loss of productivity (Mariani and Ferrante, 2017; Ferrante and Mariani, 2018).

Temperature, humidity, atmospheric pressure, light intensity, and wind speed can also be helpful in correlating sensed soil data with environmental information. Such measurands are summarized in Table 8.

3.3.2.1 Temperature and humidity

A common type of temperature sensors is the Negative Temperature Coefficient (NTC) thermistor¹⁷. A NTC thermistor correlates resistance with temperature; as resistance increases, temperature decreases.

Relative humidity relates the current absolute humidity to highest possible absolute humidity based on the current temperature. In capacitive humidity sensors, humidity affects the permittivity of the dielectric constant¹⁸. In resistive humidity sensors, the resistance of the conductive film contained in the sensor changes inversely based on the humidity.

Both the DHT11¹⁹ and DHT22²⁰ comprise of a NCT measurement component and a resistive-type humidity sensor. The DHT11, seen in Figure 3D, has a temperature sensing range

17 <https://www.ametherm.com/blog/thermistors/temperature-sensor-types>

18 <https://www.linquip.com/blog/types-of-humidity-sensors/>

19 <http://www.aosong.com/en/products-21.html>

20 <http://www.aosong.com/en/products-22.html>

of -20°C – 60°C with an accuracy of $\pm 1^{\circ}\text{C}$ and a humidity sensing range of 5–95% with an accuracy of $\pm 5\%$. The temperature measurement range of the DHT22 is from -40°C to 80°C for an accuracy of $\pm 0.5\%$; the humidity ranges from 0 to 99.9% for an accuracy of $\pm 2\%$.

The Si7021 I²C is a monolithic CMOS integrated circuit combining humidity and temperature sensors. The humidity range of 0–80% is provided with an accuracy of $\pm 3\%$. The temperature range of -10°C – 85°C has an accuracy of $\pm 0.4^{\circ}\text{C}$.

Similarly to the DHT11 and DHT22, the C10-M53R is a resistive²¹ humidity sensor²². It has a humidity sensing range of 20–90% with an accuracy of $\pm 5\%$.

3.3.2.2 Atmospheric pressure

In atmospheric pressure applications, absolute pressure measurements are used. This type of pressure relates pressure values to a vacuum.

A few types of pressure sensors use capacitive and piezoresistive sensing modality. The capacitive pressure sensor has a flexible membrane which will deflect depending on the pressure applied, affecting the capacitance. The piezoresistive pressure sensor has a thin diaphragm that changes the resistance as pressure is applied to the diaphragm²³.

The MPX4115A is an absolute, piezoresistive air pressure sensor²⁴. It operates within a temperature range of -40°C – 125°C and measures a pressure within the range of 15–115 kPa with an accuracy of $\pm 1.5\%$ (from 0°C to 85°C).

The BMP180 pressure sensor also uses piezoresistive technology²⁵. It operates within a temperature range of -40°C to 85°C and measures a pressure within the range of 30–110 kPa with an accuracy of 12 Pa.

3.3.2.3 Light intensity

There are a few ways to measure light including the total energy of incoming light (short wave radiation) and photosynthetically active radiation (PAR) (van Iersel et al., 2013). Short wave radiation measures most of the spectrum of radiation from the sun whereas PAR only measures wavelengths ranging from 400 to 700 nm which is the spectrum range used by plants for photosynthesis (van Iersel et al., 2013). Short wave radiation measures solar radiation flux density using a pyranometer, and PAR measures photon irradiance using quantum sensors (van Iersel et al., 2013).

The light sensor BH1750 is a digital ambient light sensor integrated circuit using an I²C bus²⁶. It is a photodetector that measures the ambient light present and has a measurement variation of $\pm 20\%$ and an operating temperature range of -40°C – 85°C . Although the authors in (Zhang et al., 2017) used this sensor for agricultural purposes, it is typically used for adjusting LCD screens and keypad back light not in the electronics industry.

3.3.2.4 Rain

Different types of information can be measured in relation to rainfall such as the presence of rain or the amount of rainfall within a period of time (van Iersel et al., 2013). The amount of rain fallen for a certain duration can be determined with a rain gauge (van Iersel et al., 2013). A version of this is a tipping bucket rain gauge. This involves rain being collected and funneled into a lever-like container. When one side fills, it tips to the other side draining all of the water it has collected and activating a switch (van Iersel et al., 2013; Tabada and Loretero, 2019). The number of times the switch is activated can be counted to calculate the amount of rainfall (van Iersel et al., 2013; Tabada and Loretero, 2019).

In general, a rain sensor detects if it is raining by measuring the resistance of the sensing board. The sensing board has copper tracks on the surface that works as a potentiometer where the resistance will depend on the water on the surface²⁷. The rain sensor used in (Patokar and Gohokar, 2018) uses this type of rain sensing board connected to a control circuit board with a comparator that can adjust the sensitivity using a potentiometer. The main limitation of this sensor is that it is only sensing if it is currently raining instead of the amount of rain that has fallen, arguably a more important measurement in agricultural settings.

3.3.2.5 Wind

Wind affects evapotranspiration in plants and can cause soil erosion and animal mortality (van Iersel et al., 2013; Perks et al., 2018). Wind is typically measured using anemometers including cup anemometers, hot-wire anemometers, and ultrasonic anemometers (Wu et al., 2021). In cup anemometers, the wind rotates the cups at a rate proportional to the wind speed²⁸. An example of a cup anemometer can be seen in Figure 3Ei. Hot-wire anemometers use a thin, electrically heated wire which cools down as a result of the wind (Morris and Langari, 2012). The cooling effect reduces the resistance allowing the wind speed to be determined (Morris and Langari,

21 https://cdn-learn.adafruit.com/assets/assets/000/035/931/original/Support_Documents_TechnicalDocs_Si7021-A20.pdf

22 http://c1170156.r56.cf3.rackcdn.com/UK_SHN_C10-M53R_DS.pdf

23 <https://www.avnet.com/wps/portal/abacus/solutions/technologies/sensors/pressure-sensors/types>

24 <https://www.nxp.com/docs/en/data-sheet/MPXAZ4115A.pdf>

25 <https://cdn-shop.adafruit.com/datasheets/BST-BMP180-DS000-09.pdf>

26 <https://www.mouser.com/datasheet/2/348/bh1750fvi-e-186247.pdf>

27 <https://www.watelectronics.com/rain-sensor/>

28 <https://www.metoffice.gov.uk/weather/guides/observations/how-we-measure-wind>

2012). These are not typically used in high wind areas as the thin wire could break (Morris and Langari, 2012; van Iersel et al., 2013). Ultrasonic anemometers use the property that airspeed affects the speed of an ultrasonic signal to get from one transducer to another (van Iersel et al., 2013). As these sensors have no moving or fragile parts, they tend to be used in areas of extreme weather conditions. An example of one of these sensors can be seen in Figure 3Eii.

3.3.3 Plant phenotypes

Plant phenotypes refer to observable characteristics in plants such as height and leaf area (Walter et al., 2015). A plant phenotype is determined by the environment and its genotype, or genetic background (Walter et al., 2015). Currently most plant phenotyping is done with imaging and remote sensing however, the advances made in computer vision and machine learning techniques have started being applied to plant phenotyping (Walter et al., 2015; Li et al., 2020). In (Li et al., 2020) the authors provide an overview of current techniques for image-based plant phenotyping. Moreover, there is research into developing smart plant wearables that can monitor plant health at a finer resolution than with remote sensing (Yin et al., 2021). Plant wearables can monitor the microclimate as well as plant measurements such as water potential, strain of plant tissue, and volatile organic compounds (Nassar et al., 2018; Yin et al., 2021). Plant growth is one of the measurements that can be obtained with these wearables using strain sensors based on piezoresistive, piezoelectric, and capacitive effects (Nassar et al., 2018; Lee et al., 2021)

Not very many papers studied in this review article provide information regarding plant measurements. Those that did use CMOS sensors and image processing techniques. In (Patokar and Gohokar, 2018) plant growth is monitored by taking images after specified time intervals. The authors in (Zhang et al., 2017) calculated the function leaf angle and chlorophyll concentration to judge if a plant is in good health. Function leaf angle measures leaf movement (Zhang et al., 2017). In a weak plant the function leaf angle is less than in a healthy plant (Zhang et al., 2017). Chlorophyll concentration also gives an indication to a plant's health where higher chlorophyll concentration is correlated to a healthier plant (Zhang et al., 2017).

3.4 Discussion

Precision agriculture has been able to give farmers the necessary information to make informed management decisions on their farms based on spatial and temporal data. This allows them to make an efficient use of resources without affecting yield. However, most of these practices are concerned with monocropping. Although reducing the amount of farm input does positively affect the environment, there is more that

can be done to sustain the growing population while protecting the environment.

Current practices in precision agriculture show the potential for efficient farming. This can be exploited in other farming practices, and land management uses, such as in agroforestry. In addition, there is a need for better methods for soil nutrient sensing. These measurements could provide farmers with important information on fertilizer use and prevent the negative effects of excess fertilizers.

4 Precision livestock farming

By 2050, the use of animal products is expected to double (Schillings et al., 2021). The increasing population and decreasing number of farmers puts a strain on animal farming resulting in larger herd sizes and challenges in herd management (Berckmans, 2014; Berckmans, 2017; Schillings et al., 2021). The larger herd sizes raises concerns over disease transfer from animals to humans (Berckmans, 2014). Moreover, livestock farming has a high environmental impact attributing over 92% of ammonia emissions (Berckmans, 2014). There are also growing concerns over animal welfare as demonstrated by the Animal Health Law in the European Union adopted in 2016²⁹ (Berckmans, 2017; Aquilani et al., 2022).

Precision livestock farming (PLF) aims to assist in the management of livestock through the use of real-time, continuous monitoring of animal health, welfare, production and reproduction, and environmental impacts (Berckmans, 2017). Through the use of real-time and continuous monitoring, PLF can detect small yet significant changes in animal behaviour and warn the farmer when something goes wrong allowing for early action (Berckmans, 2017; Aquilani et al., 2022). PLF can assist in increasing productivity with less inputs (Berckmans, 2017). Furthermore, the continuous and real-time monitoring can provide customers a guarantee of food safety and quality along the supply chain (Berckmans, 2014, 2017).

This section takes a look at sensors used in precision livestock farming, their advantages and disadvantages, and what they have to offer data-driven agroforestry.

4.1 PLF measurements

There are several attributes that can be measured to assist in the management of livestock. Based on the recently published review (Aquilani et al., 2022) these are summarized here.

- Animal identification

²⁹ https://ec.europa.eu/food/animals/animal-health/animal-health-law_en

- Body weight measurements
- Animal location
- Detecting animal behaviours
- Virtual fencing
- Reproductive monitoring

There are several methods of animal identification that have been recently reviewed in (Aquilani et al., 2022). Electrical identification systems typically use radio frequency identification tags (RFID) which transmit information to a tag reader (Aquilani et al., 2022). Examples of information that can be stored include animal growth, medication, drinking or eating habits and so on (Aquilani et al., 2022). RFID tags can be grouped into boluses, ear tags, and injectable glass tags, although ear tags are the most widely used (Aquilani et al., 2022).

Body weight measurements are necessary in livestock farming to determine production and stocking rates, for instance (Wangchuk et al., 2018). The commonly used weighing scale, although accurate, is time-consuming, costly and stressful to the animals (Wangchuk et al., 2018). Walk-over-weigh platforms can be placed in restricted entry points, for instance for feed, water, or milking (Dickinson et al., 2013; Aquilani et al., 2022). These platforms combined with RFID technology can allow for identifying the animal and recording their weight with no unnecessary animal handling, reducing animal stress (Dickinson et al., 2013; Aquilani et al., 2022). Apart from walk-over-weigh platforms, image analysis can also be used to estimate body weight (Aquilani et al., 2022). However, these techniques have mostly been tested in indoor settings (Aquilani et al., 2022).

Real-time and continuous information on animal location can give the farmer instant information about where every animal in the herd is located. This is typically done using GPS tracking or with top-view cameras (Aquilani et al., 2022). The use of GPS may not always be realistic due to their current high cost especially if they are needed for each animal; however, there is work in reducing the cost of these (Aquilani et al., 2022). In addition, there is the possibility of having some animals fitted with Bluetooth devices instead of GPS, thus reducing the overall cost (Aquilani et al., 2022). Furthermore, GPS tracking is limited by its battery lifespan making it unsuitable for animals not often handled by humans (Aquilani et al., 2022). There is work in this area to use solar panels, or kinetic energy to power the GPS tracker. Another limitation of using GPS for animal tracking, is the loss of reception that can occur due to topography or weather (Aquilani et al., 2022). To work around these limitations, top-view cameras can also be used alongside image processing techniques to monitor the herd (Aquilani et al., 2022). However, it has been noted that animal size and topography affect sensitivity and precision (Aquilani et al., 2022). The use of top-view cameras significantly lowers the cost compared to the cost of the use of GPS tracking (Aquilani et al., 2022).

Animal welfare can be determined through the understanding of animal behaviour, which includes grazing behaviour, animal-to-animal interaction, or jaw movements for feed or drink intake (Schillings et al., 2021; Aquilani et al., 2022). Sensors for detecting animal behaviour can include GPS, accelerometers, inertial measurement units (IMU), pressure sensors, and acoustic sensors (Aquilani et al., 2022).

Virtual fencing is used for controlled grazing (Aquilani et al., 2022). Farmers can make and change boundaries where the animals can graze replacing the need for physical fencing allowing greater flexibility to the farmer in choosing grazing areas (Aquilani et al., 2022). Virtual fences can also reduce labour, improve management of the herd, and enhance the protection of environmentally-sensitive areas (Campbell et al., 2019). When animals approach a boundary their GPS mounted collar plays a sound to let the know they should stop, if ignored the animal is given an electric shock (Aquilani et al., 2022). There is concern over animal welfare regarding the electric shock, however using only audio cues is not as effective (Aquilani et al., 2022).

PLF can also be used for reproductive monitoring by alerting the farmer when an animal is ready to reproduce or has started parturition (Aquilani et al., 2022). The need for remote oestrus detection is based on the breeding management of the farm (Aquilani et al., 2022). For planned breeding, real-time sensing of the oestrus cycle is necessary (Aquilani et al., 2022). Typically done in the past with pedometers and accelerometers, recent work has been done using wireless intravaginal probes for cattle measuring conductivity, temperature, movement, and position. Parturition can be important to detect especially if quick intervention is needed (Aquilani et al., 2022). This can be detected in sheep using GPS and accelerometers placed on the tail of animals for identifying behaviour changes such as walking speed and direction.

In (Aquilani et al., 2022), the authors provide information about the commercially available solutions for monitoring and managing livestock, and for studying behaviour.

4.2 Discussion

Advantages of PLF include the ease of managing and monitoring a big herd. This is especially useful in pasture based systems where the farmer's contact with the animal tends to be less frequent (Aquilani et al., 2022). The ability for an automatic, continuous, and real-time monitoring will become increasingly important as herd sizes increase in the future (Berckmans, 2017; Aquilani et al., 2022). In addition, the continuous monitoring of individual animals using wearable sensors, for example, allows for the understanding the animal's baseline behaviour. Small changes in behaviour that may not be obvious to an observer can allow for early detection of diseases or injuries and allow for early intervention (Schillings et al., 2021).

This can minimize the spread of diseases and minimise painful experiences for animals thus increasing animal welfare (Schillings et al., 2021).

Generally, PLF will decrease the amount of contact the farmer has with the animal. This lack of positive contact can affect the human-animal relationship affecting productivity and animal welfare (Schillings et al., 2021). Furthermore, PLF suffers the same limitations as precision agriculture in terms of the limitation of its technology, such as cost and battery life span (Aquilani et al., 2022).

In conclusion, precision livestock farming has the ability to support management decisions and early interventions through the use of real-time, continuous monitoring of livestock affecting animal welfare, production and reproduction rates, and the environmental impact of livestock farming. Similarly to precision agriculture, PLF can also give farmers the tools to increase production while reducing inputs by understanding the animal's needs.

Both precision agriculture and precision livestock farming rely on the use of sensors and wireless sensor networks to manage plants and livestock through real-time monitoring techniques. The techniques used in PLF, just like for PA, can be exploited for other agricultural practices, such as in silvopastoral agroforestry systems.

5 Principles of permaculture

The term permaculture was coined in the mid 1970s by Bill Mollison and David Holmgren (Holmgren, 2002). Originally defined as a method of sustainable, or permanent, agriculture, permaculture has since evolved to a holistic design process for complex systems and design of social systems (Holmgren, 2002; Krebs and Bach, 2018). Permaculture is now defined as “consciously designed landscapes which mimic the patterns and relationships found in nature, while yielding an abundance of food, fibre and energy for provision of local needs” (Holmgren, 2002). It conceptualises the design of sustainable socio-ecological land use systems, recognizing that they are interlinked with social systems (Holmgren, 2002; Krebs and Bach, 2018). Three basic ethical design principles are used to guide and provide an organisational framework (Holmgren, 2002):

- Care for the earth (soil, biodiversity, living things)
- Care for people (care for self and others)
- Limit to consumption and reproduction, and redistribute surplus.

The foundations of these principles are inspired by the observation of natural processes (Hirschfeld and Acker, 2021). The performance of crops or livestock in terms of yield and nutrition is directly related to the environment and any

intervening inputs (Hirschfeld and Acker, 2021). Industrialized agriculture has a short-term gain in efficiency, but the regular use of synthetic fertilizers and pesticides compromise environmental integrity impeding the longevity of these systems (Hirschfeld and Acker, 2021). In contrast as a result of its design principles, permaculture emphasizes crop diversity, the use of perennial and annual crops, and organic or chemical-free management of the soil and plants (Krebs and Bach, 2018; Hirschfeld and Acker, 2021).

5.1 Permaculture and agroforestry

As a result of the permaculture design principles, permaculture utilises a mix of crops with perennials (Krebs and Bach, 2018). However, permaculture also encapsulates a wider concept: the relationship of mankind with nature, and the design and redesign of all natural resource management systems, so that they support the health and well-being of all present and future generations (Holmgren, 2002). That being said, agroforestry can help meet the needs of the permaculture design principles (Krebs and Bach, 2018).

5.2 Permaculture and precision farming

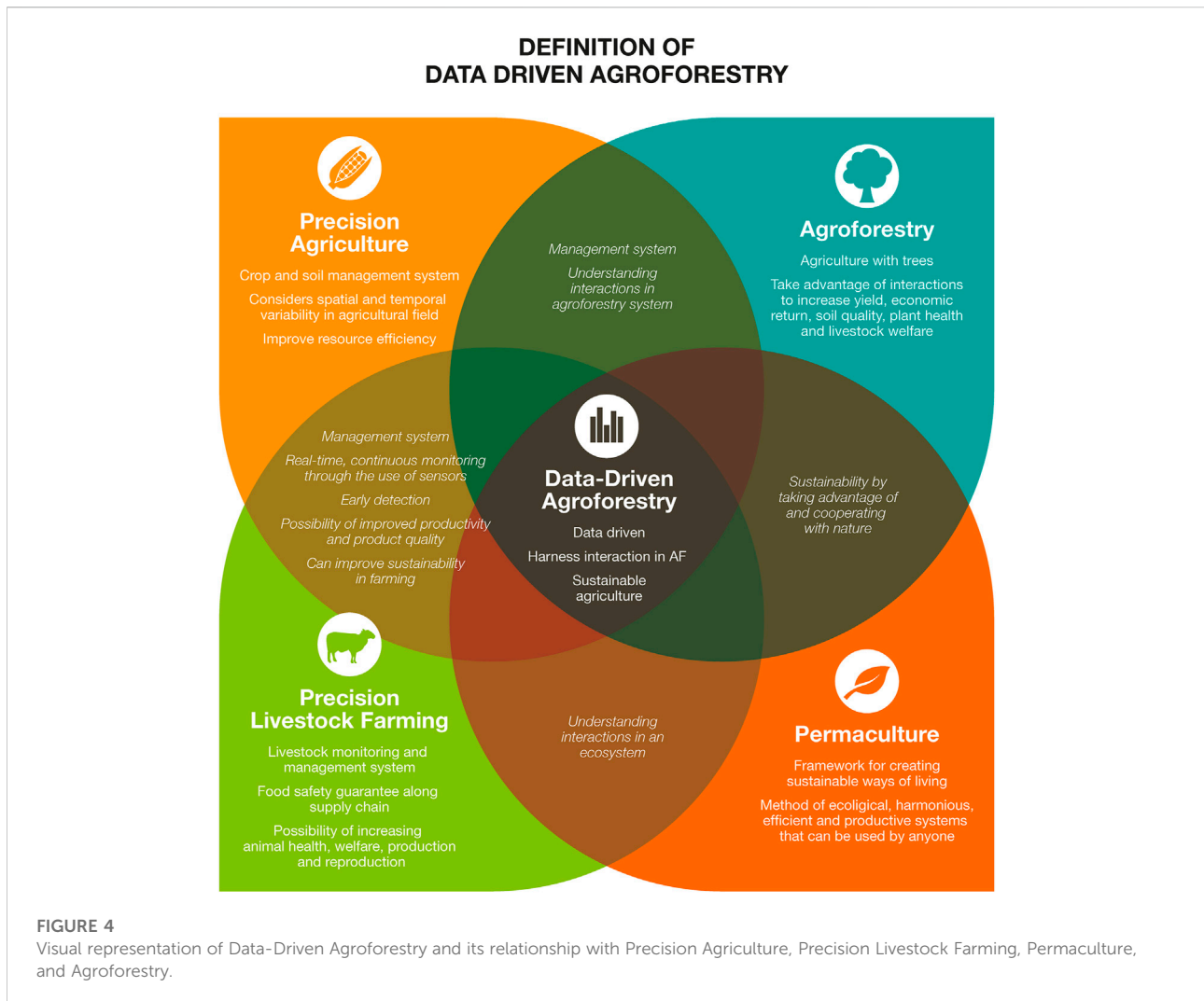
Limited research has been carried out concerning the use of sensor technology for permaculture. The authors of (Ismail and Seddik, 2014) developed and tested a low cost and low power WSN in a laboratory environment. They did not propose sensors to measure certain properties for a given goal or output of the permaculture system. Moreover, the authors describe permaculture as sustainable farming instead of viewing it as a more holistic approach.

Although not using *in situ* sensing, the authors in (Flores et al., 2020) demonstrate the capability of using an unmanned aerial vehicle (UAV) in permaculture to monitor biodiversity, system component interactions, land cover and land use, and landscape heterogeneity over time using aerial photography. This could potentially be a good starting point for more advanced sensing techniques.

6 Data-driven agroforestry

Section 2 demonstrated the lack of real-time spatial and temporal data in agroforestry systems. Sections 3, 4 presented the potential of precision agriculture and precision livestock farming in providing data to allow farmers the ability to better manage their farm. An overview of the holistic approach offered by permaculture was provided in Section 5.

This review article proposes a new field of research called Data-Driven Agroforestry (DDA) which combines the



sustainable and holistic aspect of permaculture with the data-driven approach used in PA and PLF so that these principles can be applied to agroforestry systems. This approach can allow farmers to harness the interactions in an agroforestry system to their benefit while using a sustainable agricultural method that will provide numerous benefits to their crops, trees, and livestock. [Figure 4](#) provides a visual representation of data-driven agroforestry, and its overlap with precision agriculture, precision livestock farming, permaculture, and agroforestry.

6.1 Measurand suggestions

Based on the information collated in [Sections 2, 3, 4](#), [Figure 5](#) gives a representation of the possible measurands for soil, plants, productivity, microclimate, biodiversity, and animal welfare. Details of the additional measurands needed

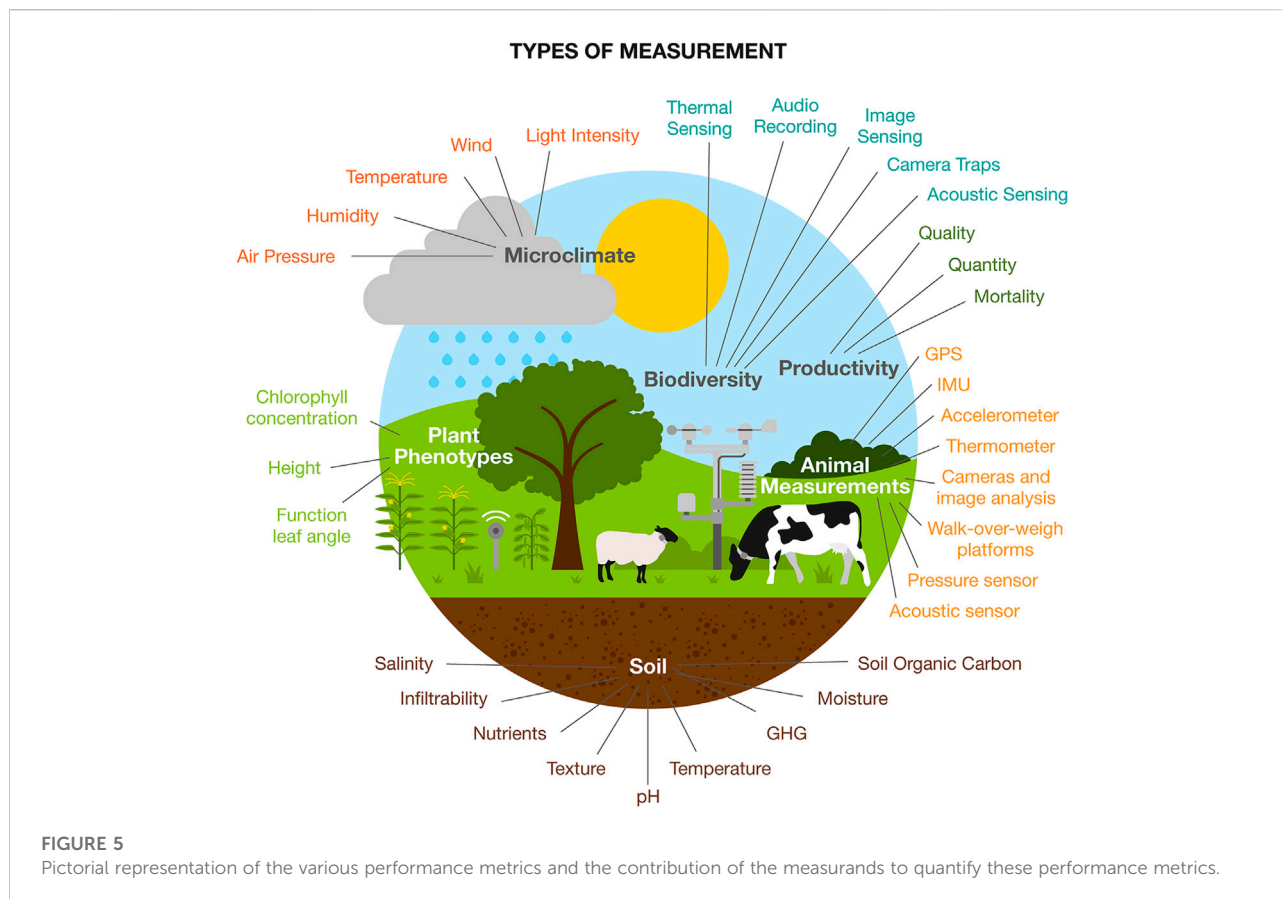
in data-driven agroforestry are provided in the relevant subsections.

6.1.1 Productivity

Productivity deals with the economic profit that could be generated by the system including crop, tree, livestock yield, and decrease of mortality. Quality of the final product can help determine the economic return. This performance metric uses the raw measurements obtained by the sensors and interpret them in the light of the local socio-economic conditions of the agroforestry system.

6.1.2 Biodiversity

Measuring insects and animals can determine variations of biodiversity in an agroforestry system. In addition, the determination of quantification of pests can allow for better management of pesticides ([Lima et al., 2020](#)). Such systems include thermal, image, and acoustic sensing ([Shafi et al.,](#)



2019; Lima et al., 2020). Further sensing and detection of other animal and insects can be done with camera traps and audio recording devices (Muller-Karger et al., 2018).

6.1.3 Microclimate

Microclimate sensing includes environmental humidity, temperature, atmospheric pressure, light intensity, and wind speed. As the review for precision agriculture shows, most of these sensors are already widely used and could be readily applied in DDA systems.

6.1.4 Animal measurements

The change in microclimate in agroforestry systems due to the addition of trees, can offer protection to livestock from the weather (Perks et al., 2018). This can increase animal comfort thus improving animal welfare and productivity (Lemes et al., 2021). The addition of trees encourages natural animal behaviour like foraging and provides an alternate food sources for livestock, reducing the cost for feeding and the emissions that come with producing animal feed (Perks et al., 2018; Augère-Granie, 2020). Furthermore, trees can remove ammonia and nitrate from the environment thus potentially reducing the overall environmental impact of livestock farming (Perks et al., 2018).

As discussed in Section 4, animal monitoring methods include the use of GPS, Bluetooth, RFID tags, accelerometers, pressure and acoustic sensors, and cameras and image processing techniques. These technologies can help farmers manage livestock within data-driven agroforestry systems.

6.1.5 Plant measurements

As previously mentioned, the addition of trees can alter the microclimate and create competition of resources which could have effects on the crops or plants (Rao et al., 1997; Hislop and Claridge, 2000). Monitoring plants and crops can help identify and rectify any issues as they arise thus allowing for better the management of the agroforestry system. Section 3.3.3 discusses some methods of measurements for understanding a plant's health in precision agriculture which could benefit DDA.

6.1.6 Soil measurands

Environmental measurands in agroforestry systems were considered in Section 2.3.2. From the review in precision agriculture, soil measurements, such as soil moisture and soil temperature, have the potential to determine soil health and understand the interactions within the soil that lead to these environmental benefits. However, some measurands that could

TABLE 9 Performance metrics, measurands, and sensors that could be potentially used in data-driven agroforestry. PLF based on Aquilani et al. (2022). Not commercially available (NCA).

Precision Agriculture (PA)				Agroforestry (AF)				Precision Livestock Farming (PLF)							
Category	Measurand	Modality	Sensor	Category	Measurand	Modality	Sensor	Category	Measurand	Modality	Sensor	Product Name			
Soil	Moisture	Capacitance	EC-5	Biodiversity	Animal and pest detection	Acoustic	NCA	Cattle	Weight	Walk-over-weigh	G06000 Gallagher	Datamuster			
		Capacitance	10HS			Thermal	NCA		Temperature	Thermometer	smaXtec				
		Capacitance	SEN0193			Imaging	NCA		Accelerometer		Ceres Tag				
		Resistance	FC-28		Pollinators	Development needed	Accelerometer			smaXtec					
		Resistance	Watermark		Growth	Imaging	NCA		Accelerometer		SensHub				
	Resistance	SEN13322	Piezoresistive		Piezoelectric	NCA	Heat		Accelerometer	Moomonitor+					
pH	Current	Atlas pH probe	Plant	Health	Imaging	NCA	Accelerometer			IceTag & IceQube					
Temperature	Digital thermometer	Capacitance					NCA		Accelerometer		Moocall				
Temperature	Capacitance	Si7021					Soil		GHG	Micrometeorological Chamber	NCA	Accelerometer		Ceres Tag	
			Resistance	DHT11	Accelerometer							smaXtec			
	Resistance	DHT22	Chamber	NCA	Accelerometer							SensHub			
	Humidity	Capacitance	Si7021	Remote sensing	NCA	Accelerometer				Moomonitor+					
		Resistance	DHT11	Nutrient concentration	Development needed	Accelerometer			IceTag & IceQube						
		Resistance	DHT22			Accelerometer			Halter						
Resistance		C10_M53R	Microclimate	Atmospheric pressure	Piezoresistive	MPX4115S	Accelerometer		Vence						
Light intensity	Photodetector	BH175FV1					Walk-over-weigh	G06000 Gallagher	Datamuster	Accelerometer		smaXtec			
										Rain	Tipping bucket	DL-TBRG	Accelerometer		SensHub
													Resistance	RD01	Accelerometer
Wind	Cup anemometer	PCE-A420					Calving	Accelerometer		Accelerometer		eShepherd			
										Hot-wire anemometer	Testo 405	Fencing	GPS	Ceres Tag	
	Ultrasonic anemometers	Windsonic M										GPS		Halter	
Pig	Weight	Image analysis					Phone camera	Pigwei							
	Cattle, sheep, goat	Activity					Accelerometer	NoFence							
Fencing		GPS					NoFence								
Cattle, sheep, goat, horse	Activity	Accelerometer					digitanimal								
	Fencing	GPS	digitanimal												

be useful in data-driven agroforestry did not come up in the review of sensors used in precision agriculture, possibly due to the lack of or absence of these *in situ* sensors. These include soil organic carbon, soil infiltration, soil nutrients and soil greenhouse gas emissions.

In (Chen et al., 2020) the authors propose measuring soil organic carbon using *in situ* visible near-infrared spectroscopy. They concluded that, coupled with deep learning algorithms, the sensing modality has the potential for large-scale soil organic carbon monitoring (Chen et al., 2020). In (Huang et al., 2019) the authors use a peristaltic pump, camera, and computer with a mathematical model to estimate the soil water infiltration. None of the papers studied in the review specify the pH sensors, however these are widely used (Ananthi et al., 2017).

Soil can also store and emit greenhouse gasses (GHG) including carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄) (Oertel et al., 2016; Yamulki, 2017). Some of these greenhouse gas emissions are due to aerobic production in the stems and branches by microorganisms, and through soil produced gases that are transported through the stem (Yamulki, 2017). Measurements that can affect soil GHG emissions include soil moisture, temperature, pH, UV radiation, and plant or tree species just to name a few (Oertel et al., 2016; Yamulki, 2017). Measuring the soil GHG emissions is necessary for better quantifying global greenhouse gas budgets which can benefit decisions for land management (Oertel et al., 2016; Yamulki, 2017). The review in (Oertel et al., 2016) includes a review of soil GHG measurement methods such as chamber systems, micrometeorological methods, remote sensing, airborne methods, and laboratory approaches.

Chamber methods are the most common for measuring GHG (Butterbach-Bahl et al., 2016; ISO 20951, 2019). There are two main types of chambers: open and closed (Butterbach-Bahl et al., 2016). Open chambers measure the gas concentration at the inlet and outlet and the gas flux can be calculated by taking the difference of concentrations at the two measurement points (Yu et al., 2013). There are two types of closed chambers: static and dynamic. Closed static chambers typically operate manually where samples are taken and analyzed in a laboratory (Heinemeyer and McNamara, 2011). On the other hand, closed dynamic chambers are a closed loop system that tend to be automated and *in situ* (Heinemeyer and McNamara, 2011; Yu et al., 2013). These methods only account for GHG emissions of the small area of the field where the measurements are taken. Furthermore, due to their inherent intrusiveness, chamber systems have the potential to alter soil and microclimate conditions affecting the measured concentrations (Görres et al., 2016). In addition, in most chamber systems, CO₂ measurements tend to be underestimated due to the headspace increase during the sampling period (Heinemeyer and McNamara, 2011; Yu et al., 2013). However, these tend to be most noticeable in

closed, static chambers (Heinemeyer and McNamara, 2011). On the other hand, chambers are easy to use and useful for assessing short term changes (Jalota et al., 2018).

Paper (Görres et al., 2016) compares two commercial soil GHG dynamic chamber systems the LI-8100A³⁰ and AGPS³¹. The LI-8100A is an automated system for measuring CO₂. It has a multiplexer allowing for either one or multiple chambers and uses an infrared gas analyzer to measure CO₂ and H₂O concentrations. The AGPS³¹ is an automatic vial collector, but was fitted with a multiplexer and gas analyzer for the study (Görres et al., 2016). Alternatively, the GT5000 Terra³² and DX4015³³ are gas analysers that can also be used to calculate GHG in soil. They both use Fourier transform infrared spectroscopy (FTIR) to identify gases and their concentrations.

Another method is the eddy covariance method, a micrometeorological method, which measures vertical turbulent fluxes of water, CO₂, heat, CH₄, and volatile organic components in the atmosphere (Jalota et al., 2018). Differently from the chamber method, this technique can measure GHG over a large area and without disturbing the soil (Jalota et al., 2018). However, it has a high operational cost and is dependent on weather conditions such as air turbulence (Jalota et al., 2018).

6.2 Discussion

Based on the reviews of precision agriculture, precision livestock farming and agroforestry, Table 9 was generated which shows the measurands, sensing modalities and examples of sensor used in precision agriculture, agroforestry, and precision livestock farming. This table shows a striking lack of knowledge transfer between these different areas. Precision agriculture and precision livestock farming have a lot to offer to provide farmers a data-driven approach to agroforestry. Taking advantage of this can fill the current gaps in agroforestry research by providing a temporal and spatial, real-time understanding of an agroforestry system. However, as noted from Table 9, there is a need for further development in areas such as measuring biodiversity, soil nutrient content and GHG emissions, and plant growth and health that could assist in gathering important information for DDA and help in the management of agroforestry systems.

30 <https://licor.app.boxenterprise.net/s/jtpq4vg358reu4c8r4id>

31 https://www.uit-gmbh.de/en/product-details___762/getProdInfos_-_1795/

32 <https://www.gasmet.com/wp-content/uploads/2019/09/Gasmet-GT5000-Terra-Technical-Datasheet-ID-10233.pdf>

33 <https://www.gasmet.com/uk/wp-content/uploads/sites/10/2018/03/Gasmet-DX4015-Technical-Data-ID-7090.pdf>

7 Conclusion and future work

This paper presented an up-to-date review of agroforestry and precision agriculture. Table 9 identifies gaps in the current research. Firstly, there is a need for *in situ* real-time, autonomous sensing of soil nutrients and soil GHG. Current methods for these measurements are destructive and expensive, thus are unsuitable for data-driven agroforestry. In addition, there is the need for commercialised plant growth and health sensors, as well as for biodiversity sensing. Overall, most measurements for agroforestry rely on laboratory analysis of samples. From the review of AF, there were limited occurrences of measurements with sensors.

The review for precision agriculture gave an overview of the sensors used in wireless sensor networks in agriculture and their use for specific performance metrics. This information helped come up with the proposed measurements and sensors that could be used in data-driven agroforestry. Similarly, the precision livestock farming section gave information about the types of attributes measured and the method of measurement in PLF. Next, an overview of permaculture was presented and compared to precision farming and agroforestry. Lastly, data-driven agroforestry was presented. This method of agriculture combines PA and PLF practices with agroforestry providing an understanding of the real-time interactions that occur within agroforestry. Based on the agroforestry, PA, and PLF reviews, proposed measurements and sensors were identified that could be used in data-driven agroforestry.

Data-driven agroforestry has the potential to help farmers harness the interactions occurring between the different components of the system for a multitude of benefits such as increased yield, environmental benefits, and animal welfare. In addition, it can promote a more sustainable agricultural method that can eventually sustain population growth as witnessed today.

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Author contributions

EB, MD, and JH contributed to the conception of this work. EB conducted the review and prepared the manuscript under the supervision of MD, JH, KB, and DA. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

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