A New Paradigm for Sustainable Development in Agriculture: Mathematics & AI Get Into the Field

Book of Abstracts

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Contents

The workshop

Technological tools offered by modern Artificial Intelligence carry the promise to make modern agricultural practices more efficient and sustainable. The related scientific challenges are multiple and complex, and require extensive and interdisciplinary skills.

Nested into the SEED PRECISION project (PRecision crop protECtion: deep learnIng and data fuSION) funded by Università degli Studi di Milano, the workshop aims to be an opportunity of exchange between researchers of different fields involved in this innovation: Mathematics, Computer Science and Agricultural Engineering.

The organizers gratefully acknowledge *La casa dell'Agricoltura* for the precious help in building up this workshop, The Department of Environmental and Science Policy, Università di Milano and the European Consortium for Mathematics in Industry (ECMI).

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Integration of remote sensing and mobile technologies to derive nutritional status maps for VR top-dressing fertilization

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This study aimed at developing an operational service (PocketNNI-Sat) to support variable rate (VR) top-dressing nitrogen (N) fertilization based on the integration of remote sensing and mobile technologies. The rationale is to overcome the limitations of satellite imagery and proximal technologies for estimating N nutritional status [1] when used alone, by benefiting from the strengths of the former in capturing spatial variability and of the latter in providing information with a clear biophysical meaning.

The service – providing 10 m-resolution N nutrition index (NNI, Eq.(1)) maps – derives from the approach proposed and evaluated by Nutini et al. [2], which is based on the following steps: (i) analyzing Sentinel 2 NDRE (normalized difference red edge) images to identify few (2 to 6) points in the field able to capture the largest variability; (ii) using a mobile phone to collect in each of the points (smart scouting) estimates of plant N content (PNC) and leaf area index (LAI); (iii) deriving relationships between PNC estimates in the points and NDRE values in the corresponding Sentinel 2 pixels; (iv) deriving relationships between LAI estimate in the points and NDVI (normalized difference vegetation index) values in corresponding pixels; (v) using relationships derived in steps iii and iv to convert NDRE and NDVI values of all other pixels in PNC and LAI values, respectively; (vi) converting the resulting LAI map in Ncrit map according to (2) [3]; (vii) deriving the NNI map from the PNC and Ncrit ones according to (1). Step ii is performed using two mobile apps (integrated in PocketNNI-Sat) for estimating LAI [4] and leaf greenness [5], the latter being converted in PNC values using integrated variety/hybrid-specific calibration curves.

$$\mathrm{NNI} = \frac{\mathrm{PNC}}{\mathrm{Ncrit}} \tag{1}$$

$$\mathrm{Ncrit} = \frac{\mathrm{Nmat}}{1 - e^{k\mathrm{LAI}}} \tag{2}$$

In (2), Nmat is the plant N content at maturity and k is the extinction coefficient for solar radiation.

The activities dealing with interfacing with ESA portal, processing satellite images and smart scouting field measurements, and deriving NNI maps are performed automatically in the cloud, whereas the farmer uses a standard mobile phone for georeferencing field borders and collecting PNC and LAI estimates. Neither external support nor specific skills are needed to apply the whole procedure, the farmer being completely autonomous. Indeed, compared to Nutini et al. [2], the workflow has been completely automatized and implemented in an IT infrastructure that farmers can access with their mobile phone. The service is available for rice and maize for which it is operationally used from the 2021 campaigns and it is being extended to tomato and wheat.

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Counting in agriculture using deep learning algorithms

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Many agricultural applications involve a counting component, usually used as a first step towards a more complex task. For example, counting apple flowers is used to evaluate the tree's flowering intensity, for better chemical thinning [1, 2]. Counting of plants' leaves is used to evaluate their growth stage [3], counting of fruits is used for yield estimation (e.g., [4]) and counting of fish is used for monitoring growth and feeding decisions [5].

With the advance of deep learning and its wide employment, an important question is - are we getting close to human level? Recently, we tried to address this question by comparing detection algorithms with several average annotators, over 7 different datasets [6]. The results will be presented along with details of algorithms developed. Using a deep learning based counting component, especially in the agricultural environment, requires some level of image processing expertise and raises several challenges. The multitude of different data types (e.g. top-view images using UAV, depth information, hyperspectral imaging) requires special treatments. Moreover, there are several counting strategies, which differ both in architecture and in the needed annotations. To reduce the needed effort in future studies and enable wider usage of deep learning algorithms we are currently developing a state-of-the-art counting framework for deep learning practitioners and researchers.

We will present results of several successful studies, along with the initial structure of the counting framework.

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PANTHEON: An H2020 Project on the Precision Farming of Hazelnut Orchards

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In this talk an overview of the results of the H2020 project PANTHEON will be given. Briefly, PANTHEON is an European project focused on the precision farming of hazelnut orchards. In this regard, PANTHEON idea is to develop the agricultural equivalent of an industrial Supervisory Control And Data Acquisition (SCADA) system for the precision farming of hazelnut orchards. The proposed SCADA architecture consists of unmanned aerial and ground robots that collect data and perform farming activities. All the information is collected in a central unit that performs automatic feedback actions (e.g. suckers management) and supports the decisions of the agronomists (e.g., pruning suggestions). The capabilities of the proposed SCADA architecture have been validated within a a real-world (1:1) hazelnut orchard located in the Tuscia area (province of Viterbo, Italy).

Precision Farming of Hazelnut Orchards: Agronomic decision making

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The Project PANTHEON, funded by the European Community Horizon 2020 programme under grant agreement 774571, aims to develop the agricultural equivalent of an industrial Supervisory Control And Data Acquisition (SCADA) system to be used for precision farming applications on large hazelnut (Corylus avellana L.) orchards. Through the use at field scale of properly equipped terrestrial and aerial robots, remote sensing application and big-data management, the overall objective is to design an integrated system where a relatively limited number of heterogeneous unmanned robotics components move within the orchards to collect data and even perform some farming operations [1].

The information will be stored in a central operative unit that will integrate the data coming from the different robotic units to perform automatic feedback actions (e.g. to regulate the irrigation system) and to support the decisions of agronomists and growers. Compared to the current status in precision farming application on hazelnut orchards [2], the proposed SCADA infrastructure could represent a relevant step ahead in the context of the orchard management.

Some crop operations such as hazelnut sucker control, irrigation, pruning and pests and diseases control have been selected as a model [3], in order to develop the SCADA infrastructure. Furthermore, the early nut yield estimation has been attempted through the development of a mathematical model which considered the unique way in which this perennial species fruits [4]. Among the activities carried out in synergy by the project consortium researchers, the agronomic decision support component is highlighted, in order to adequately develop field trials, algorithms for intervention automation and machine learning activities. These activities, with particular reference to those of plant management (sucker control and pruning) and yield estimation are dealt in this contribution.

In conclusion, the main expected benefits of this SCADA approach are the opportunity of increasing hazelnut production and simultaneously decreasing in chemical and water inputs usage, and significantly simplify the orchard management.

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A Deep Learning Generative Model Approach for Image Synthesis of Plant Leaves

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We generate via advanced Deep Learning (DL) techniques artificial leaf images in an automatized way. We aim to dispose of a source of training samples for AI applications for modern crop management. Such applications require large amounts of data and, while leaf images are not truly scarce, image collection and annotation remains a very time–consuming process. Data scarcity can be addressed by augmentation techniques consisting in simple transformations of samples belonging to a small dataset, but the richness of the augmented data is limited: this motivates the search for alternative approaches. Methods. Pursuing an approach based on DL generative models, we propose a Leaf-to-Leaf Translation (L2L) procedure structured in two steps: first, a residual variational autoencoder architecture generates synthetic leaf skeletons (leaf profile and veins) starting from companions binarized skeletons of real images. In a second step, we perform translation via a Pix2pix framework, which uses conditional generator adversarial networks to reproduce the colorization of leaf blades, preserving the shape and the venation pattern. Results. The L2L procedure generates synthetic images of leaves with a realistic appearance. We address the performance measurement both in a qualitative and a quantitative way; for this latter evaluation, we employ a DL anomaly detection strategy which quantifies the degree of anomaly of synthetic leaves with respect to real samples. Conclusions. Generative DL approaches have the potential to be a new paradigm to provide low-cost meaningful synthetic samples for computer-aided applications. The present L2L approach represents a step towards this goal, being able to generate synthetic samples with a relevant qualitative and quantitative resemblance to real leaves.

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High Order Singular Value Decomposition for Plant Diversity Estimation

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Starting from NASA multi-spectral images to estimate plant diversity we evaluate diversity and we compare original diversity estimates with those realized via the High Order Singular Value Decomposition (HOSVD) of tensors compression methods for big data. Our strategy turns out to be extremely powerful in terms of memory storage and precision of the outcome. I will briefly present the ecological framework and then I will mainly focus on the mathematical aspects.

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Detecting spacio-temporal patterns from temporal remote sensing data in Precison Agriculture

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Specific-site management (SSM) is the management of agricultural crops at a spatial scale smaller than that of the whole field. SSM techniques are relatively new in agriculture – its implementation, in the 1980's, begun as a response to the need to control costs in large scale mechanized agriculture. Since then, its focus has evolved and now SSM techniques are also recognized and recommended (see [1]) for their contribution to a sustainable agricultural that does not marginalize profit.

Specific-site management methods require withinfield spatial variability to be identified and measured. The problem of identifying and delineating areas with different properties is designated as the management zone delineation problem (MZsP). The identification of the management zones is achieved mostly through clustering techniques rooted on soil or vegetation indices sample information. Vegetation indices are indices extracted from light spectra that can be be used to monitor the state of the crop, as plants reflect light differently according to their health condition. Thus, crop canopy multispectral reflectance is a good indicator of features such as growth, vigor, water content of and others. This information allows scarce resources can be allocated where needed, enabling better quality and lower cost.

In this talk, we describe an algorithm to delineate management zones by measuring the variability of crop condition within the field through the analysis of time series of geo referenced vegetation indices. More precisely, our approach, proposed in [2, 3], uses a evolutionary algorithm to mine spatio - temporal clusters from time series of vegetation indices extracted from Sentinel-2 imagery. Each cluster represents a behaviour pattern of a vegetation indices for a particular subset of spatio coordinates through a specific set of times. The temporal component of this analysis permits MZs dynamics to be characterized within timeframes in the growing season. Data from maize and vineyard crops in Alentejo have been used to assess the suitability and accuracy of the algorithm with good results. It is expected that these patterns help to identify the most suitable moments to apply fertilizers or pesticides, furthermore, the forecast of the crop production could be done based on those patterns.

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Hybrid Modelling in Agriculture

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Hybrid modelling is the integration of different modelling approaches [1] and in particular the combination of differential equations (ODE and/or PDE) into individual-based models (IBM), two antithetical yet complementary views of systems. The hybrid modelling approach has the big advantage of simulating complex systems as sets of different modules, which can be implemented in different mathematical approaches most appropriate to render the subsystem under consideration. On the other hand, hybrid modelling also comes with a reduction in analytical capabilities to understand model behaviour, for it relies on distinct, apparently incompatible formalizations (algorithmic vs mathematical, discrete vs continuous time, etc). In this context we present the hybrid modelling approach applied to two different agricultural systems such as plant- pathogen interactions:

- Olea europaea – Bactrocera oleae
- Vitis vinifera – Plasmopara viticola

• • In the case of Bactrocera oleae we present a model that represents the different phenological phases of the pathogen (egg, larva, pupa, adults) in two sites with different environmental conditions, while the model of Plasmopara viticola also describes the different levels of alarm for the farmer.

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Integrating Robotics and AI for Practicing Precision Agriculture

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Robots are perceptive machines that can be programmed to perform a variety of agricultural tasks, such as cultivating, transplanting, spraying, monitoring, selective harvesting etc. Agricultural robots have the potential to enhance the quality of fresh produce, lower production costs and reduce the drudgery of manual labor. The inherent nature of agricultural robots make them suitable to perform precision agricultural tasks. However, in agriculture, the environment is highly unstructured. The terrain, vegetation, landscape, visibility, illumination and other atmospheric conditions are not well defined; they continuously vary, have inherent uncertainty and generate unpredictable and dynamic situations. As we face growing pressures on our global food system, artificial intelligence offers a roadmap for a greener and more efficient agricultural revolution. Artificial intelligence has already transformed several industries and now, capitalizing upon the huge amount of agricultural data available, holds the promise of driving an agricultural revolution. To date, however, the field of artificial intelligence and agriculture remains in a relative state of infancy. Integrating these two complementary areas, AI and robotics, will enable advanced abilities in performing precision agriculture tasks in unstructured, dynamic and variable environments.

Innovation in Smart Farming: Deep Learning-based Techniques for Plant Diseases Recognition

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Transboundary plant diseases and pests are responsible for causing significant losses to farmers and threatening food security worldwide. Monitoring the growing conditions of crops and detecting plant diseases is critical for sustainable agriculture. Traditionally, crop inspection has been carried out by people with expert knowledge in the field. However, regarding any activity carried out by humans, this activity is prone to error, leading to possible incorrect decisions. Innovation is, therefore, an essential fact of modern agriculture. In particular, deep learning has played a key role in solving complicated applications with increasing accuracy over time. Recent interest in this type of technology has prompted its potential application to address complex problems in agriculture, such as the automatic recognition of plant diseases. As part of our research works, we have proposed various techniques based on deep learning that can accurately recognize plant diseases and pests in real-world greenhouse scenarios. Our early work [1] introduced an architecture that can automatically perform localization and diagnosis of tomato diseases using bounding box and class information. Consecutively, we proposed an improved method based on a "refinement filter bank" [2] to cope with the problems of class imbalance and false positives. Additionally, we studied further implementations to provide more objective information to users, for instance, using text to describe plant anomalies [3]. Encouraged by the results achieved by our previous works, we seek further improvements, especially to make the system more adaptable to new real-world greenhouse conditions. We are particularly interested in addressing the performance decay observed when a model is evaluated in new scenarios. Therefore, our most recent works have studied these issues using the concept of open set domain adaptation and control classes to refine the generalizability of the model towards coping with complex changes in new greenhouse environments. Also, we have developed techniques [4, 5] to deal with the problem of data scarcity in agriculture by implementing generative adversarial networks to generate artificial data that can be used for data augmentation purposes. Experimental results on our tomato diseases and pest dataset collected from various greenhouses in South Korea demonstrate the efficiency and effectiveness of our proposed approaches. Furthermore, our research works have contributed to providing farmers and researchers with technology that can facilitate crop management and avoid losses, mainly through an early estimation of plant diseases.

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Crop Classification under Varying Cloud Cover with Neural Ordinary Differential Equations

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Optical satellite sensors cannot see the Earth's surface through clouds. Despite the periodic revisit cycle, image sequences acquired by Earth observation satellites are therefore *irregularly* sampled in time. State-of-the-art methods for crop classification (and other time series analysis tasks) rely on techniques that implicitly assume regular temporal spacing between observations, such as recurrent neural networks (RNNs). We propose to use neural ordinary differential equations (NODEs) in combination with RNNs to classify crop types in irregularly spaced image sequences. The resulting ODE-RNN models consist of two steps: an update step, where a recurrent unit assimilates new input data into the model's hidden state; and a prediction step, in which NODE propagates the hidden state until the next observation arrives. The prediction step is based on a continuous representation of the latent dynamics, which has several advantages. At the conceptual level, it is a more natural way to describe the mechanisms that govern the phenological cycle. From a practical point of view, it makes it possible to sample the system state at arbitrary points in time, such that one can integrate observations whenever they are available, and extrapolate beyond the last observation. Our experiments show that ODE-RNN indeed improves classification accuracy over common baselines such as LSTM, GRU, temporal convolutional network, and transformer. The gains are most prominent in the challenging scenario where only few observations are available (i.e., frequent cloud cover). Moreover, we show that the ability to extrapolate translates to better classification performance early in the season, which is important for forecasting.

Will Artificial Intelligence feed the world?

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Artificial Intelligence has started a revolution in the agricultural field as it has similarly done in the last few years in the industry. From precision agriculture to yield prediction, the availability of data and the development of novel computational techniques, together with the use of novel plant genomics and novel agricultural techniques, are making possible higher production rates with less consumption of nutrients and pesticides. This is the 2030 target of the European Union Farm2Fork Strategy, which foresees 50% reduction in the use of pesticides, 50% in reduction of nutrient losses, 50% reduction in antimicrobials, and 25% increase in organic farmed land. Among the agronomic tasks that have the greatest impact on most of these targets, it is worth citing contrast to weeds in open field and greenhouses cultures. Indeed, to reduce the use of chemicals preserving and possibly increasing yields production rate, a different approach is required.

In our talk we discuss how Artificial Intelligence techniques can play a key role for a precise and soil friendly contrast to weeds. Indeed, by the accurate detection and discrimination of weeds and crops it becomes possible to reduce the use of chemicals in intra-row weeding if not canceling it completely via precise mechanical weeding. We report the preliminary results of the Agri-food Competition for Robot Evaluation (ACRE) [1] run within the H2020 METRICS project to evaluate autonomous weeding. We report in details the results related to the weed discrimination task which involves image segmentation of weeds in maize and beans fields under different illumination and acquisition conditions (see Figure 1). While discussing the neural network architectures used for the task, we also present novel technique to deal with the possibly limited availability of data and to face the high variability of imaging conditions that might hinder the robustness and reliability of the systems.

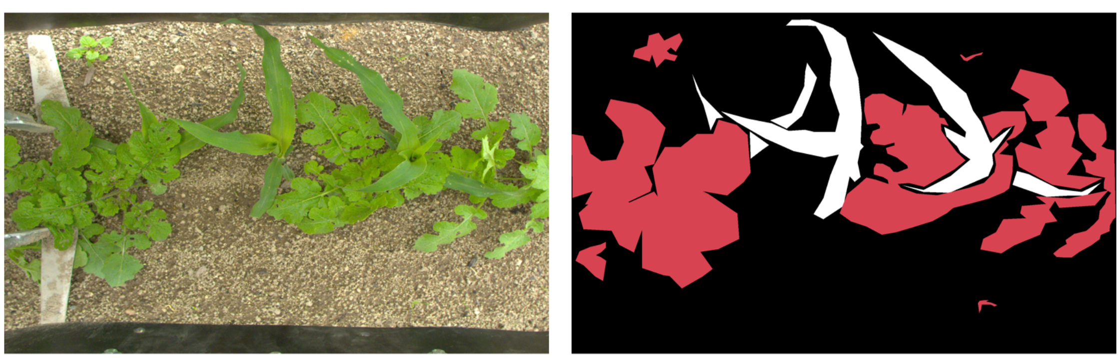

Figure 1: An example of weed (red) vs crop (white) segmentation (ground truth) in a maize field.

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Assessing the potential of Machine Learning Regression Algorithms for improving crop Leaf Area Index estimation from Sentinel-2 Data

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Spaceborne earth observation systems offer a great opportunity to collect multispectral reflectance imagery as a fundamental input to deliver cost-effective support services for agriculture. These services mainly focuses on the retrieval of quantitative information of vegetation canopy status such as Leaf Area Index (LAI). LAI is the leaf area per unit of ground surface, thus it numerically represents the size of vegetation canopy in specific conditions varying according to plants community composition, and their phenological stage and status of development. In cropping systems, LAI is a state variable based on which key processes of crop growth are regulated, photosynthesis and transpiration, in particular.

Therefore, the indirect measurement of LAI by reflectance-based sensors, since many years, is addressed as crucial step for assessing spatial and temporal variability of crop canopy and making available quantitative information to drive farmers in crop management through an optimized use of agricultural inputs. Despite the large number of attempts to retrieve LAI from multispectral satellite images, current solutions are not yet able to efficiently quantify all those specific conditions, which are requested for agricultural applications, influencing crop variability in time and space.

With this speech, we aim to stimulate the discussion about the potential of Machine Learning Regression Algorithms (MLRA) for improving LAI retrieval [1] by Sentinel-2 multispectral data, with respect to common empirical methods based on Vegetation Indices (VIs). For this purpose, we show main results from an in-field research carried out over two growing seasons (2018 and 2019), on three crops (i.e., winter wheat, maize, and alfalfa), characterized by different growing cycles and canopy structures, grown in three different farms [2]. The accuracy of methods based on semi-empirical relation with best performing VIs and MLRA for LAI estimation was assessed at both pixel and field levels over mixed-crop (MC) and crop-specific (CS) data sets. Overall, MLRA approaches showed a higher accuracy of prediction at pixel level than VIs-based ones. Moreover, among the different MLRA tested Gaussian Process Regression (GPR) showed the best accuracy to predict LAI over a mixed-crop dataset. These results lead to conclude that: 1) MLRA may improve the quantitative representation of within-field LAI variability; 2) GPR may improve LAI estimation without an a priori knowledge of land cover/use.

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Traceability of tomato condition using deep transfer learning neural networks

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Tomato is one of the most popular vegetables consumed by humans and is consumed by millions of people every day. As the world's population grows, tomato cultivation must meet growing demand levels. In agricultural science, automation improves the country's quality, economic growth and productivity. Thanks to deep learning, the classification of images through computer systems of artificial intelligence is becoming more and more feasible, which means that computer systems can recognize and classify images with a high degree of accuracy, exceeding human capabilities. Traditional systems based on conventional knowledge are unable to meet current production management requirements for precision selection because they are time consuming and have frequent failures. This paper proposes an automated tomato cultivation classification method in the context of its traceability for quality control and optimal management. Therefore, our research concerns an improved deep learning categorization method that enhances accuracy and reduces tomato sorting time by a relatively small amount of training data. We implemented a classification system based on the convolutional neural network (CNN) AlexNet [1], by performing transfer learning and then training and validating our model in a dataset of images with tomatoes. The image classification system can be applied in the harvest phase. Thus, two scenarios of automatic categorization of the fruits of tomato cultivation emerge, aiming at its optimal management. The first scenario concerns the classification of the crop into ripe- unripe, while the second scenario concerns the healthy-diseased part. The transfer learning based on AlexNet CNN achieves tomato defect discrimination by 82.5

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