

Lecture Notes in Civil Engineering

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Innovative Biosystems Engineering for Sustainable Agriculture, Forestry and Food Production

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Preface

The Mid-Term Conference of the Italian Association of Agricultural Engineering (AIIA) is part of a series of conferences, seminars and meetings that AIIA periodically promotes and organizes, also together with other entities and associations, involving stakeholders, public and private, with the aim of facilitating the encounter of research and training, innovation and development demand, and to promote the creation and dissemination of new knowledge in the sector.

This particular 2019 Mid-Term AIIA Conference will deal with the following major topic:

Innovative Biosystems Engineering for Sustainable Agriculture, Forestry and Food Production

The specific subjects will include the following:

- Agricultural hydraulics;
- Water resources management in agriculture and forestry ecosystem;
- Design and management of Farm and District-Scale Irrigation Systems;
- Remote Sensing in agricultural and forestry systems;
- Monitoring and modelling of the interactions among soil hydrological, plant and atmosphere;
- Processes, and agricultural management practices;
- Soil and contaminant hydrology;
- Forestry hydraulics and hydraulics protection of agricultural and forestry systems;
- Bioengineering Techniques for soil protection and slope stabilization;
- Rural buildings, facilities and territory;
- Spatial and landscape analysis;
- Planning and design of rural areas;
- Mechanization and technologies for agricultural production;
- Agricultural electrification and energy usage;

- Ergonomics and work organization;
- Computer and communication technologies;
- Machines and facilities for agricultural products and food processing.

The sustainable development of agriculture, forestry and food production sectors is closely related to the research developments in the field of biosystems engineering.

On one side, biosystems research is oriented to efficiently produce and process biological resources to satisfy the demand of consumers and a wide range of industries for food, feed, bioenergy and bio-based products. At the same time, it provides and develops engineering-based methodologies and decision support tools for management and protection of soil, water and environmental resources; design of structures, facilities, equipment and infrastructures; planning and design of rural areas and landscape; mechanization and technologies for agricultural production; agricultural electrification and energy usage; ergonomics and work organization and safety; computer and communication technologies.

The aim of this Conference is to stimulate contributions related to the engineering technological applications to the agriculture, forestry and agri-food sectors. Researchers involved in activities related to Biosystems and Agricultural Engineering, as well as Agricultural, Forestry and Food Engineers, farm and food company managers have been invited to present their contributions at the Conference.

This book focuses on the challenges to implement sustainability in diverse contexts in the fields of biosystems engineering for sustainable agriculture, forestry and food production. As the production systems are mainly based on the agricultural sector, the research has taken up the challenge of the sustainable use of renewable and non-renewable resources showing some possible solutions in order to have a sustainable production.

The book consists of seven parts, offering a broad and multidisciplinary approach of some interesting solutions in the field of innovative biosystems engineering, each part corresponds to the seven technical sections composing the AIIA association.

- Part I—Land and Water Use;
- Part II—Rural Buildings, Equipment and Territory;
- Part III—Mechanization and Technologies for Agricultural Production;
- Part IV—Agricultural Electrification and Use of Energy;
- Part V—Ergonomics and Work Organization;
- Part VI—Machines and Plants for Processing Agricultural Production;
- Part VII—Information and Communication Technologies.

We wish to thank colleagues and technicians who participated in the Conference and supported us. We would like also to thank all the authors who have presented their contributions to the Conference. Finally, we would like also to express our

gratitude to the President of the AIIA Association and to the Presidents of the seven AIIA Sections who have taken the responsibility to organize the review and revision of the presented works making thus possible the realization of this book.

Potenza, Italy

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Giuseppe Altieri
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Introduction

The contribution of agricultural and biosystems engineering to meet the sustainable agriculture challenges and contributing to economic growth

The Italian Association of Agricultural Engineering (AIIA)

AIIA was founded in 1959, as a national association belonging to the Commission Internationale du Génie Rural (CIGR). AIIA adheres to the CIGR in all its direct and indirect forms and represents it nationally. AIIA also adheres to the European Society of Agricultural Engineers (EurAgEng), a European member of the CIGR. Furthermore AIIA, along with other scientific societies pertaining to the agricultural, forestry, agro-industrial and environmental sectors, is a part of the Italian Society of Agricultural Scientific Societies (AISSA). The AIIA coordinates and develops all the activities in the field of agricultural and biosystems engineering, i.e. those scientific and technical disciplines related to engineering applied to agricultural and forestry systems. Moreover, AIIA promotes the exchange of experiences and research results among scholars and professionals. AIIA fosters initiatives involving the application of engineering principles to the processes at the basis of land use and territorial development in order to study, model and enhance biological systems for sustainable agriculture, food production, land use and environment safety. AIIA is particularly active in networking between scholars and experts in the various sectors of agricultural and biosystems engineering, with reference to research, innovation, development, technology transfer and training. AIIA periodically promotes and organizes, also together with other institutions and associations, conferences, seminars and meetings involving stakeholders, public and private, with the aim of facilitating the encounter of research and training, innovation and development demand, and to promote the creation and dissemination of new knowledge in the sector.

In particular, the Italian Association of Agricultural Engineering pursues the following aims:

- Bring its technical and scientific contribution to questions of general interest in the field of agricultural engineering;
- Foster relations between scholars and operators dedicated to agricultural engineering;
- Promote the development of agricultural engineering in its various branches;
- Encourage, coordinate and perform—also on behalf of third parties—research in the field of agricultural engineering, also by setting up specific centres;
- Encourage the training of technicians specialized in agricultural engineering by means of teaching courses, scholarships and similar facilities;
- Promote activities and events for dealing with historical and cultural issues concerning agricultural engineering;
- Promote and maintain connections with similar Italian and foreign institutions;
- Promote study events for dealing with issues and problems of a scientific and technical nature relevant to agricultural engineering.

The *Journal of Agricultural Engineering* (JAE), an international journal with peer review and open access, is the official organ of the Association.

The Italian Association of Agricultural Engineering is divided into the following Technical Sections:

- Part I—Land and Water Use;
- Part II—Rural Buildings, Equipment and Territory;
- Part III—Mechanization and Technologies for Agricultural Production;
- Part IV—Agricultural Electrification and Use of Energy;
- Part V—Ergonomics and Work Organization;
- Part VI—Machines and Plants for Processing Agricultural Production;
- Part VII—Information and Communication Technologies.

Members of AIIA are professors and researchers of Universities and Research Institutes, and scholars, experts, technicians, professionals, companies active in research and training in the field of agricultural and biosystems engineering in Italy.

Giacomo Scarascia Mugnozza
President of the Italian Association
of Agricultural Engineering (AIIA)

The Context

In the past century, considerable advances were made in discovering fundamental principles in several scientific disciplines, which created major breakthroughs in management and technology for agricultural systems. However, in the twenty-first century, agricultural research has more difficult and complex problems to solve. Growing environmental awareness of the general public is challenging producers to change farm management practices and protect water, air and soil quality, while staying economically profitable. At the same time, market-based global competition

in agricultural production and global climate change are threatening the economic viability of traditional agricultural systems, and now require the development of dynamic new production systems. Site-specific optimal management of spatially variable soils and available water resources, associated with optimal selection of crops, can help achieve both production and environmental objectives. Fortunately, new technologies can provide a vast amount of real-time information about soil and crop conditions via remote sensing or ground-based instruments which, combined with near-term weather forecasting, can be utilized to develop a whole new level of site-specific management.

Agricultural engineering recognizes the importance of multidisciplinary approaches to develop and deliver know-how and technological solutions in tackling problems at full scale, in real-time and on real-life systems, (Munack 2000).

The used approaches share much common ground with environmental concerns, and the development of methods and systems to deal with the underlying biological system complexity and uncertainty is a major scientific challenge. Agricultural systems are often sensitive to many interacting environmental variables and processes, and solutions frequently involve understanding, monitoring and controlling complex processes in order to improve productivity and minimize environmental emissions and impacts.

The Vision in the Twenty-First Century

There is today real demand for further innovation and its translation into practice in the agricultural context. A wide range of physical sciences and engineering disciplines can make a substantial contribution to the future of agriculture. The following Table 1 provides a synopsis of the sciences involved in different agricultural/environmental applications.

Table 1 Agricultural engineering applications in the context of wider sciences (Source Munack 2000)

	MATHEMATICAL MODELING	SENSORS	REMOTE SENSING	NANOTECHNOLOGY	FLUID DYNAMICS	SOIL PHYSICS	DATA MINING AND PATTERN	ROBOTICS	SURFACE CHEMISTRY
PRODUCT QUALITY	X	X						X	X
ENVIRONMENTAL POLLUTION	X	X	X		X	X			
LOGISTICS	X							X	
ENVIRONMENTAL CONTROL	X	X			X				
IRRIGATION MANAGEMENT	X	X	X		X	X	X	X	
FERTILIZERS AND PESTICIDES				X			X		X
WITHIN-FIELD PRECISION		X					X	X	
SELECTIVE HARVESTING			X					X	
POST-HARVEST MANAGEMENT		X							
LIVESTOCK SYSTEMS	X	X	X	X	X		X	X	
SOIL AND WATER MANAGEMENT	X	X	X		X	X	X		X

Advances in sensing, control engineering, mechanical and hydraulic engineering, robotics and mechatronics, data management, will all contribute to global challenges solutions (Cavalli and Monarca 2011; Scarascia Mugnozza et al. 2011; Gandolfi and Lenzi 2011). Similarly, the ways in which engineering advances will demonstrate their impact is very varied. The sections below serve to emphasize opportunities in different areas of application.

Precision Agricultural Management

Precision Crop Management and Harvesting

(i) Advanced sensing techniques will provide real-time information on the health status of crops (nutrient levels, presence of disease) and soils (nutrient levels); (ii) Appropriate combination of data with crop and system models, will provide early warning of risks and suggest mitigation strategies; (iii) Appropriate interpretation of the relationship between spatial variability of biochemical–physiological response of plants and vegetation, which can be detected by remote sensing observation, and of the stress factors (water, nutrient and salinity stress) may help to adopt spatially variable crop management to maximize productivity and minimize wastage of inputs; (iv) With robotics systems increasingly available, crop quality sensing at harvest will allow to optimize harvest time and sorting to be integrated with the harvesting process.

Precision Control of Pest and Disease

(i) Biosensors will provide early warning of pest or disease outbreaks; (ii) Further improvements to chemical application, through innovative atomization and improved spray handling, will allow optimizing target coverage and efficacy by minimizing losses and environmental impact; (iii) Mechatronics and automation technologies will allow crop management with autonomous machines, including the identification and eradication of weeds by non-chemical means.

Precision Livestock Management

Controlling Animal Health and Welfare

(i) Guidance to animal management both in the field and in housed systems will be improved by animal monitoring systems, including environmental sensors, machine vision, acoustic monitors and gas detectors; (ii) Biosensors will be actively used for monitoring key health and welfare indicators in real time; (iii) Coupling direct observations on the performance of individual animals and animal growth models, will provide early health warning systems to identify and control nutrition and environmental problems.

Controlling Environmental Impacts

(i) Innovative housing and aeration design will improve the control of ventilation and the aerial environment for animals; (ii) Greenhouse gases and other emissions in livestock housing systems will be minimized by environmental control sensors; (iii) Innovative chemical engineering techniques will improve waste treatment and recycling of water and nutrients.

Agriculture and Environment: New Challenges for Engineers

Progress in biological sciences, associated with engineering research and innovations will provide many benefits for agricultural systems, which can be summarized as follows:

Balancing Future Demand and Supply Sustainably

Innovation in agricultural engineering is going to be a crucial contributor to the delivery of agricultural outputs under sustainable intensification conditions. New science and innovative technologies will open up new practices that will both increase production and reduce or reuse waste streams.

Advances in Precision Farming to Enhance Crop Productivity

Advances in precision farming are already supplying considerable understandings of the variability of current production systems (yields can vary considerably in different regions of the same field). Anyway, more precisely controlled input (at scales down to a few meters or individual plants) may still produce benefits in terms of increased productivity, reduced inputs and lower environmental impacts. Timings and quantities of fertilizers and pesticides can be adjusted to match current locally crop state and can be coupled to predictions of future changes in growth rates or disease pressure. Future advances in application technologies and in crop management regimes will allow minimizing gas emissions from soils. Better planning and scheduling of machine operations have the potential to reduce costs by 20%.

Improved Animal Health and Welfare Through Real-Time Monitoring and Diagnostics

Real-time monitoring will allow recognizing health and welfare problems. Biosensors to identify changes in physiological state or exposure to pathogens will become feasible for use in intensive systems, and even in extensive ones through the use of remote tracking and monitoring systems. This real-time monitoring can improve productivity and quality, while also addressing welfare and environmental

impact issues. Improved dairy cow fertility management through estrus sensing has been estimated to be able to deliver 15% reduction in methane emissions, for example.

Meeting the Challenges of a Low Emission World

Concerns about energy demand and climate change require that improvements be made in environmental control and emissions from the biological processes on which farming depends. Engineering advances to optimize performance in energy use for land management and in renewable energy production will be crucial if agriculture is to play its part in averting damage to climate and environment. The complexity of farming systems calls for an interdisciplinary approach to these problems, and combinations of new biological concepts and new engineering techniques are needed.

Reduced Emissions and Other Waste from Livestock

Innovative approaches to managing and handling waste, both on-farm and through cooperative actions with other waste generators, have the potential to enhance the return of plant nutrients to the land and maximize crop nutrient value while minimizing liquid and gaseous emissions of pollutants, including greenhouse gases. Effective management of livestock waste may also provide on-farm energy, e.g. through anaerobic digestion and pyrolysis.

Sensors based on simple physical methods or on more sophisticated techniques using near-infrared spectroscopy or hyperspectral reflectance analysis may be used to determine the nutrient content of the waste stream before land spreading, or even in real time during land spreading, so that application rates can be matched to local crop nutrient requirements within the field. Optimizing application systems will allow the manure in the soil to be distributed appropriately, to control losses of gases such as ammonia or nitrous oxide, and ensure rapid nutrient availability for the crop. High capacity distribution machinery will allow timely application within narrow periods when crop requirements, soil conditions and the demands of regulations come together.

Optimizing Energy Use in Farm Machines

Fuel economy has become a major concern to the industry following price increases, and is now strongly studied. Tractors and other agricultural machines mostly use diesel engines. These are characterized by more sustained and often continuous full-power operation and cooling concerns due to slower vehicle speed and often dusty operating conditions.

New Contributions to Assess the Interactions Among Soil Physical Processes, Plant and Atmospheric Processes, Agricultural Water Management, Soil Environment and Climate Change

Interpreting and controlling the interaction between farming systems and management processes, including soil and water processes, will allow innovative technologies to deliver real benefits to maintain ecosystem services for feeding the world.

The Soil–Plant–Atmosphere Continuum as a Hydraulic System

Water uptake is a key component of the soil hydrological balance and is of concern for a range of hydrological, agricultural and ecological applications, as it controls, either directly or indirectly, the partitioning of infiltrating water into evaporation, transpiration and deep percolation fluxes. It is a dynamic process influenced by soil, plant and climate conditions. It depends on a number of factors such as soil water pressure head, soil hydraulic conductivity, osmotic head (in saline condition), evaporative demand, rooting depth, root density distribution and plant properties. Soil physicists and hydrologists have skills to apply analytical and numerical techniques to model water flow in hydraulic systems and to quantify water transport in plants. The challenge to modelling water uptake and transport in plants is that water flow is controlled by a biological entity, the plant, which senses environmental conditions such as light, temperature and humidity, and continuously adjusts flow rates to maintain its own internal water status. Water potential gradients between the soil and the atmosphere drive the flow. This results in a dynamic hydrologic flow system controlled by both physical and biological parameters. Since plant hydrology and plant structure are closely tied, an understanding of plant hydraulic relationships is essential if we are to model plant properties like leaf and stem sizes and arrangement. A sophisticated approach to the issue would be to combine plant hydrology with an L-Systems description of plant architecture (Prusinkiewicz and Lindenmayer 1990). Forestry researchers have made advances in modelling such systems, but more work is necessary, especially in the area of xylem hydraulics (Sperry et al. 2003).

Transpiration and Carbon Dioxide Fluxes at the Vegetation-Atmosphere Interface

Most of the models simulating agro-hydrological systems should be improved with respect to the effect of water stress on transpiration, C assimilation (photosynthesis), C allocation, canopy temperature and the resulting water use efficiency for production. So far, simple stress factor approach has been mostly adopted to simulate transpiration. In some models, daily crop water stress is calculated as $1 - AT/PT$, where AT is the daily actual water uptake and PT is daily potential transpiration (Hanson 2000; Sudar et al. 1981). In principle, models should rely on stomatal resistance to simulate transpiration (see for example RZWQM model, Farahani and Ahuja 1996). Stomatal behaviour is an important regulator of water flow from the soil and plant to the atmosphere and control mechanisms are still largely unknown.

Are stomata responsive to leaf water potential or soil water potential or both, or other factors such as temperature and chemical signals? Coupled models of photosynthesis and transpiration with an energy balance hold the greatest potential to appropriately model and analyse these issues (Buckley et al. 2003; Tuzet et al. 2003). This would provide a more physiologically based approach taking into account processes that plants have developed to optimize C assimilation and minimize water loss under all conditions of water availability and especially water-deficit situations. Application of such models in forestry has provided good representations of plant response to water stress (Misson et al. 2004). Many of the parameters in these models can be determined using photosynthetic gas flux equipment and sap flow measurements.

Agricultural engineers are well qualified to tackle the above biophysics and energy balance problems.

Better Use of Irrigation Water to Support Production

Water scarcity and quality degradation are set to become the main environmental problems for all countries in the Mediterranean region in the near future. Due mainly to population growth, pressure on agriculture and demand for water to irrigate food crops have also increased. In Mediterranean countries the irrigated area has more than doubled in 40 years, totalling 24,200,000 ha in 2009 (17.8 million in Mediterranean Europe and 6.4 million in Northern Africa). However, in many countries, irrigation practice is often wasteful and highly inefficient. In an attempt to tackle the problem in Italy and other Mediterranean regions, open-channel irrigation systems have been (or are going to be) converted into pressurized pipeline networks. In most cases, the “on-demand” method for water distribution has been adopted to replace the old rotational schedule (Lamaddalena and Sagardoy 2000; D’Urso 2001; Schultz and De Wrachien 2002; Galelli et al. 2010; Coppola et al. 2019).

However, experience shows that even for on-demand pressurized irrigation systems the performance of distribution networks is still frequently far from acceptable in terms of efficiency for both (1) economic/political and (2) technical reasons.

In this context, the use of decision support systems (DSS) may significantly enhance the management of on-demand irrigation systems. Advanced technical tools are nowadays available for monitoring and simulating the various physical processes involved in an irrigation system. Such tools can be used in an integrated way for estimating irrigation water demand and scheduling water use, and thus for simulating the operation of on-demand irrigation networks, under varying soil and weather conditions, crop management options and irrigation technologies.

In general, by integrating the above technical tools with economic instruments, such systems may facilitate the decision-making process on the quantities of water to be allocated to agricultural consumers. Such tools may take into account the most profitable cropping patterns given any water restrictions imposed by existing hydrological conditions, as well as the potential yields in each irrigation district according to its production characteristics, irrigation efficiency, economic scenario and external factors such as agricultural policies.

Processes at the Watershed Scale

Going from field to watershed scale, several processes come into play, such as subsurface flow of water and chemicals to a channel or a stream, flow of field surface runoff through riparian zones, chemical transport in channels and streams. In addition, there may be related to soil erosion processes. Agricultural engineers and soil physicists can contribute to quantification and modelling of some of these processes at this scale as well. Some examples of past contributions in this area are the work on subsurface interflow (Lehman and Ahuja 1985), tile flow (Johnsen et al. 1995), gully erosion (Zheng et al. 2000), and buffer strips (Seobi et al. 2005). Watershed models have been developed that include the above processes, such as the SWAT, AnnAGNPS and REMM models (Arnold et al. 1998; Lowrance et al. 2000; Bingner and Theurer 2001). These models simplify the simulation of physical processes for large simulation units. However, agricultural engineers and soil hydrologist can help improve these simulations by ensuring that field-scale effects are appropriately aggregated up to the watershed scale.

Modelling Climate Change, Soil Environment and Agriculture

Agricultural engineers may significantly contribute to the evaluation of the contribution of agricultural practices on global warming and, inversely, the impact of climate change on soil agricultural systems. Specifically, important contributions may come in the following issues: (i) Quantifying the impact of agricultural soils and current management practices to climate change; (ii) Assessing the effects of climate change on the soil environment, crop growth and agricultural systems, and to identify potential management changes to mitigate the adverse effects.

Agricultural soils and management contribute to climate change primarily through the emission of greenhouse gases, such as CO₂, CH₄, N₂O, NO and NH₃. Models are needed to quantify these emissions as functions of several dynamic variables and aggregate the results over large spatial areas and long timescales. Some models are available (Li 2000) that need more extensive evaluation and improvement.

Climate changes have impacts on the soil environment, especially soil water and temperature, and a number of related processes, such as evapotranspiration, runoff and erosion. Models are needed to quantify these influences in different agricultural systems and to identify strategies for mitigating any adverse effects (e.g. Tubiello et al. 2000).

Land-Use Change Impacts on Floods at the Catchment Scale

Agricultural engineers may also contribute to quantify the land-use change effects on floods. The intensification of agricultural practices has heavily modified natural landscapes. Tillage has frequently created dense soil layers inducing preferential lateral flow and reducing the filtering and buffering potential of soil horizons. Hillslopes have been modified for agricultural production, thus changing flow paths, flow velocities and water storage, and consequently flow connectivity and

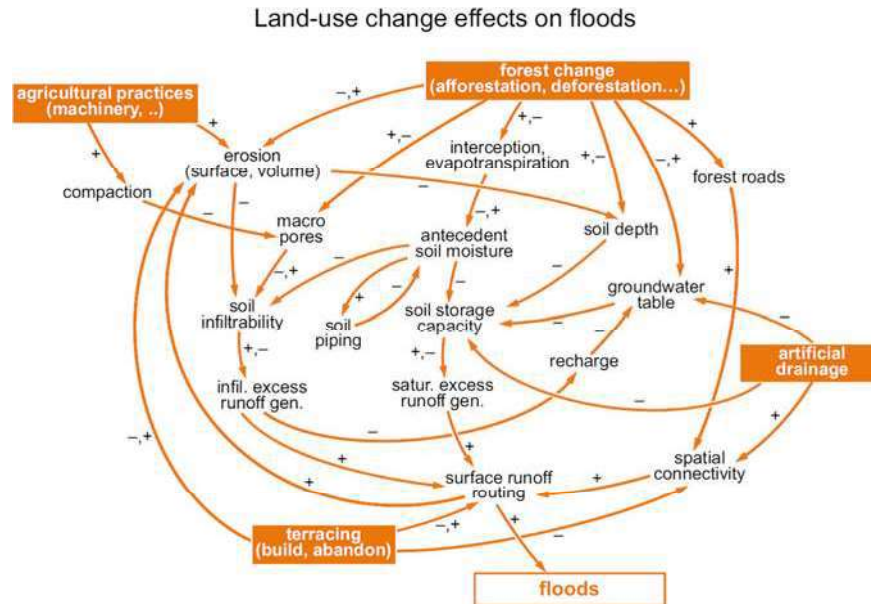


Fig. 1 Diagram of process interactions in land-use changing effects on floods at the catchment scale. Plus and minus signs indicate whether an increase in the variable increases or decreases another variable (Source Rogger et al. 2017)

concentration times. Large areas have been deforested or drained, thus either increasing or decreasing antecedent soil moisture and triggering erosion. In general, an increase in vegetation cover is expected to lead to a decrease in mean streamflow due to increased canopy interception and vegetation transpiration, and that a decrease in vegetation cover will lead to an increase in streamflow. However, the exact role of land-use change in modifying all these processes and thus the hydrological behaviour of a river basin is still to be determined. Also, our ability to predict the impacts of vegetation changes on streamflow regimes (e.g. low flow) across different spatio-temporal scales is still limited. The complexity of the issue is clearly illustrated in Fig. 1 (Rogger et al. 2017).

Concluding Remarks

The above review describes, in our judgment, the most important knowledge gaps that have been encountered by developers of agricultural and environmental system models. Acquisition of more knowledge in the above areas and its calibration will require both innovative experimental research and the development of new concepts, theories and models. Exciting and potentially high-impact areas of further research lie at the interface of several disciplines. Agricultural engineers are uniquely qualified to

tackle such challenges and make highly original and much-needed contributions. Integrated within agricultural systems, such research will create breakthroughs in the knowledge that will help solve the main practical problems that agriculture is facing in the twenty-first century. To take advantage of the opportunities indicated above it will require a supply of high-quality researchers, educators innovators, and technicians along with appropriate facilities. Therefore, we need to develop education, research and training in engineering for agriculture.

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Contents

Land and Water Use

A Comprehensive Check of Usle-Based Soil Loss Prediction Models at the Sparacia (South Italy) Site	3
V. Bagarello, V. Ferro and V. Pampalone	
Evaluating the Effects of Forest Cover Changes on Sediment Connectivity in a Catchment Affected by Multiple Wildfires	13
Lorenzo Martini, Lorenzo Faes, Cordelia Scalari, Giacomo Pellegrini, Andrés Iroumé, Mario Aristide Lenzi and Lorenzo Picco	
A Check of Water Drop Impact Effects on Surface Soil Saturated Hydraulic Conductivity	21
F. Todisco, V. Bagarello, L. Vergni and A. Vinci	
On the Description of Soil Variability Through EMI Sensors and Traditional Soil Surveys in Precision Agriculture	29
Bianca Ortuani, Enrico Casati, Camilla Negri and Arianna Facchi	
Drought Variability and Trend Over the Lombardy Plain from Meteorological Station Records	39
C. Gandolfi, A. Facchi, A. Crespi, M. Rienzner and M. Maugeri	
Biodegradable Geosynthetics for Geotechnical and Geo-Environmental Engineering	49
Alessio Cislighi, Paolo Sala, Gigliola Borgonovo, Claudio Gandolfi and Gian Battista Bischetti	
Comparison of Different Methods for Topographic Survey of Rural Canals	59
Daniele Masseroni, Daniele Passoni, Alessandro Castagna, Luca Civelli, Livio Pinto and Claudio Gandolfi	

Hydraulic Modeling of Field Experiments in a Drainage Channel Under Different Riparian Vegetation Scenarios	69
G. F. C. Lama, A. Errico, S. Francalanci, G. B. Chirico, L. Solari and F. Preti	
Groundwater Recharge Through Winter Flooding of Rice Areas	79
Arianna Facchi, Camilla Negri, Michele Rienzner, Enrico Chiaradia and Marco Romani	
Evaluation of Green Roof Ageing Effects on Substrate Hydraulic Characteristics	89
V. Alagna, V. Bagarello, P. Concialdi, G. Giordano and M. Iovino	
Influence of Site and Check Dam Characteristics on Sediment Retention and Structure Conservation in a Mexican River	99
Manuel E. Lucas-Borja, Demetrio A. Zema, Yang Yu, Mary Nichols, Giuseppe Bombino, Pietro Denisi, Antonino Labate, Bruno G. Carrà, Xu Xiangzhou, Bruno T. Rodrigues, Artemi Cerdà and Santo Marcello Zimbone	
Comparing LAI Field Measurements and Remote Sensing to Assess the Influence of Check Dams on Riparian Vegetation Cover	109
G. Romano, G. F. Ricci and F. Gentile	
SIRR-MOD—A Decision Support System for Identifying Optimal Irrigation Water Needs at Field and District Scale	117
G. Dragonetti, A. Sengouga, A. Comegna, N. Lamaddalena, A. Basile and A. Coppola	
Modeling the Effect of Different Management Practices for Soil Erosion Control in a Mediterranean Watershed	125
Giovanni Francesco Ricci, Anna Maria De Girolamo and Francesco Gentile	
The Benefit of Continuous Modelling for Design Hydrograph Estimation in Small and Ungauged Basins	133
S. Grimaldi, A. Petroselli, R. Piscopia and F. Tauro	
A Theoretical Approach to Improve the Applicability of the Catchment Connectivity Index	141
Giuseppe Bombino, Carolina Boix-Fayos, Maria Francesca Cataldo, Daniela D’Agostino, Pietro Denisi, Joris de Vente, Antonino Labate and Demetrio Antonio Zema	
On the Performance of a Novel Hybrid Constructed Wetland for Stormwater Treatment and Irrigation Reuse in Mediterranean Climate	151
Delia Ventura, Salvatore Barbagallo, Simona Consoli, Mirco Milani, Alessandro Sacco, Ruggero Rapisarda and Giuseppe Luigi Cirelli	

Rural Buildings, Equipment and Territory

- Urban Agriculture, Cui Prodest? Seattle's Picardo Farm as Seen by Its Gardeners** 163
M. E. Menconi, P. Borghi and D. Grohmann
- Evaluation of Greenwalls Efficiency for Building Energy Saving** 169
C. Bibbiani, C. Gargari, C. A. Campiotti, G. Salvadori and F. Fantozzi
- Modelling of the Thermal Effect of Green Façades on Building Surface Temperature in Mediterranean Climate** 179
I. Blanco, G. Scarascia Mugnozza, G. Vox and E. Schettini
- Heat Fluxes in a Green Façade System: Mathematical Relations and an Experimental Case** 189
Fabiana Convertino, Giacomo Scarascia Mugnozza, Evelia Schettini and Giuliano Vox
- Odor Nuisance in the Livestock Field: A Review** 199
C. Conti, M. Guarino and J. Bacenetti
- Spatial Analysis of the Impact of Rural Buildings on the Agro-Forestry Landscape Using GIS** 207
Giuseppe Cillis, Dina Statuto and Pietro Picuno
- Milk-Production in Barns with Compost Bedding and Free Stall: A Profitability Analysis** 215
Marcos A. Lopes, Gustavo R. de O. Silva, André L. R. Lima, Geraldo M. da Costa, Flávio A. Damasceno, Vítor P. Barros and Matteo Barbari
- Thermal Environment Inside Mechanically Ventilated Greenhouses: Results from a Long-Term Monitoring Campaign** 223
Andrea Costantino, Lorenzo Comba, Giacomo Sicardi, Mauro Bariani and Enrico Fabrizio
- Physical Properties of Cement Panels Reinforced with Lignocellulosic Materials** 231
Patrícia Ferreira Ponciano Ferraz, Matheus da Rocha Coutinho Avelino, Victor Rezende Carvalho, Isabela Moreira Albano da Silva, André Luiz de Lima Domingos, Rafael Farinassi Mendes, Jaqueline de Oliveira Castro, Leonardo Conti and Giuseppe Rossi
- Physical Properties of Miscanthus Grass and Wheat Straw as Bedding Materials for Dairy Cattle** 239
Patrícia Ferreira Ponciano Ferraz, Giuseppe Rossi, Leonardo Conti, Gabriel Araújo e Silva Ferraz, Lorenzo Leso and Matteo Barbari

Innovative Tensile Structures for Protected Crop Facilities	247
Silvana Fuina, Giacomo Scarascia-Mugnozza and Sergio Castellano	
Analysis of the Evolution of a Rural Landscape by Combining SAR Geodata with GIS Techniques	255
Giuseppe Cillis, Aimé Lay-Ekuakille, Vito Telesca, Dina Statuto and Pietro Picuno	
Smart Dairy Farming: Innovative Solutions to Improve Herd Productivity	265
C. Arcidiacono, M. Barbari, S. Benni, E. Carfagna, G. Cascone, L. Conti, L. di Stefano, M. Guarino, L. Leso, D. Lovarelli, M. Mancino, S. Mattoccia, G. Minozzi, S. M. C. Porto, G. Provolo, G. Rossi, A. Sandrucci, A. Tamburini, P. Tassinari, N. Tomasello, D. Torreggiani and F. Valenti	
A Methodology to Support Planning and Design of Suburban Agricultural Areas	271
P. Russo, P. Lanteri and A. D’Emilio	
Modeling Soil Thermal Regimes During a Solarization Treatment in Closed Greenhouse by Means of Symbolic Regression via Genetic Programming	279
A. D’Emilio	
Comparison of the Efficiency of Plastic Nets for Shading Greenhouse in Different Climates	287
Dina Statuto, Ahmed M. Abdel-Ghany, Giuseppe Starace, Paolo Arrigoni and Pietro Picuno	
Planning the Flows of Residual Biomass Produced by Wineries for Their Valorization in the Framework of a Circular Bioeconomy	295
Canio Manniello, Dina Statuto, Andrea Di Pasquale and Pietro Picuno	
Effects of Feeding Frequency on the Behavior Patterns of Dairy Cows in an Automatic Feeding System	305
G. Mattachini, A. Finzi, E. Riva and G. Provolo	
Shading Screens Characterization by Means of Wind Tunnel Experiments and CFD Modeling	313
E. Santolini, D. Torreggiani and P. Tassinari	
Damages to Rural Buildings and Facilities Observed in the Aftermath of 2012 Emilia Earthquakes	323
M. Bovo, A. Barbaresi, D. Torreggiani and P. Tassinari	

Proposal of a Web-Based Multi-criteria Spatial Decision Support System (MC-SDSS) for Agriculture	333
Giuseppe Modica, Maurizio Pollino, Luigi La Porta and Salvatore Di Fazio	
The Apulian Territory and the Typical Local Farmhouses: A Case of Study Through Landscape Analysis	343
E. Liano, I. Blanco and G. Scarascia Mugnozza	
Enhancement of the Roman Bridge of Canosa in the Ofanto Valley Rural Landscape	351
Enrico Liano, Silvana Fuina, Marcio A. Alberti and Giacomo Scarascia-Mugnozza	
Mechanization and Technologies for Agricultural Production	
Economic and Environmental Performances of a New Double Wheel Rake	363
J. Bacenetti, L. Bava, D. Lovarelli, A. Fusi and G. Repposi	
Environmental Impact Alternatives for Soil Tillage and Sowing: Farmer or Contractor?	373
J. Bacenetti, D. Facchinetti, D. Lovarelli and D. Pessina	
A Biomass-Fueled Flamer for In-Row Weed Control in Vineyards: An Economic Evaluation	381
Gianfranco Pergher, Rino Gubiani and Matia Mainardis	
N-TRE: A Model for the Evaluation of the Narrow Tractors Real Efficiency	389
Lavinia Eleonora Galli, Davide Facchinetti and Domenico Pessina	
Controlled Mechanical Ventilation to Reduce Primary Energy Consumption in Air Conditioning of Greenhouses	399
C. Perone, P. Catalano, F. Giametta, G. La Fianza, L. Brunetti and B. Bianchi	
Efficiency of Tractor Drawbar Power Taking into Account Soil-Tire Slippage	409
M. Cutini, M. Brambilla, C. Bisaglia, D. Pochi and R. Fanigliulo	
Design and Assessment of a Test Rig for Hydrodynamic Tests on Hydraulic Fluids	419
Daniele Pochi, Roberto Fanigliulo, Renato Grilli, Laura Fornaciari, Carlo Bisaglia, Maurizio Cutini, Massimo Brambilla, Angela Sagliano, Luigi Capuzzi, Fulvio Palmieri and Giancarlo Chiatti	

Evaluation of Potential Spray Drift Generated by Different Types of Airblast Sprayers Using an “ad hoc” Test Bench Device	431
M. Grella, P. Marucco and P. Balsari	
Influence of Ploughshare Wear on Plough Efficiency	441
Giovanni Molari, Massimiliano Varani and Michele Mattetti	
Brotweg—A Path of Bread in an Alpine Environment: New Mechanical Solutions for Grain Processing in Steep Mountain Slopes	449
Sabrina Mayr, Riccardo Brozzi, Alice Cervellieri, Thomas Desaler, Raimondo Gallo, Josef Gamper, Bernhard Geier, Laurin Holzner, Pasqualina Sacco and Fabrizio Mazzetto	
The H2020 INNOSETA Project	457
Fabrizio Gioelli, Paolo Marucco, Floriana Nuzzo and Paolo Balsari	
Sprayer Inspection in Sicily on the Basis of Workshop Activity	463
Emanuele Cerruto, Giuseppe Manetto, Domenico Longo and Rita Papa	
Evaluation on the Stability of Tree Used as Anchors in Cable Yarding Operations: A Preliminary Test Based on Low-Cost MEMS Sensors	473
L. Marchi, O. Mologni, S. Grigolato and R. Cavalli	
Modelling of Agricultural Machinery Trends for Power, Mass, Working Width and Price	481
Francesco Marinello, Tatevik Yezekyan, Giannantonio Armentano and Luigi Sartori	
High Accuracy Site-Specific Secondary Data for Mechanical Field Operations to Support LCA Studies	491
Marco Fiala and Luca Nonini	
Assessment of Forest Biomass and Carbon Stocks at Stand Level Using Site-Specific Primary Data to Support Forest Management	501
Luca Nonini, Calogero Schillaci and Marco Fiala	
Sensors and Electronic Control Unit for Optimize Rotary Harrow Soil Tillage Operation	509
Francesco Marinello, Filippo Pegoraro and Luigi Sartori	
LIFE-Vitison: An EU Project for the Set-up of VRT Organic Fertilization in Vineyard	519
Domenico Pessina, Davide Facchinetti and Lavinia Eleonora Galli	
Real-Time Measurement of Silage Moisture Content During Loading of a TMR Mixer Wagon: Preliminary Results	531
V. Perricone, A. Costa, A. Calcante, A. Agazzi, M. Lazzari, G. Savoini, M. Chiara, E. Sesan and F. M. Tangorra	

The Response Surface Methodology as a Tool to Evaluate the Effects of Using Diesel-Biodiesel-Bioethanol Blends as Farm Tractor Fuel	539
Marco Bietresato, Carlo Caligiuri, Anna Bolla, Massimiliano Renzi and Fabrizio Mazzetto	
An Approach to the Development of an Integrated Real-Time Engine Test System for Agricultural Machines: Conceiving, Implementation, Set-up and First Tests	551
Marco Bietresato, Matteo Malavasi and Fabrizio Mazzetto	
Development and Implementation of an Ultra-Low Volume (ULV) Spraying Equipment Installed on a Commercial UAV	563
Alberto Sassu, Luca Ghiani, Antonio Pazzona and Filippo Gambella	
Agricultural Electrification and Use of Energy	
Life Cycle Impact Assessment of Carrot Cultivation and Processing: An Italian Case Study for a Small Family Company in the Marche Region	575
A. Ilari, D. Duca, G. Toscano, V. Vecchiarelli and E. Foppa Pedretti	
Does Precision Photovoltaic Irrigation Represent a Sustainable Alternative to Traditional Systems?	585
Giuseppe Todde, Maria Caria, Antonio Pazzona, Luigi Ledda and Luis Narvarte	
Development of an Energy Efficiency Index for Agricultural Tractors Based on OECD Codes Data	595
C. Carnevali and S. Angelelli	
Evaluation of Coaxial Pipes for Basal Heating as Alternative for Energy Saving in Heating System for Leafy Vegetables	603
M. Fedrizzi, C. Terrosi, S. Cacini, G. Burchi, M. Cutini, M. Brambilla, C. Bisaglia, M. Pagano, S. Figorilli, C. Costa and D. Massa	
Energy Monitoring of Fully Automated Dairy-Farm: A Case Study	611
Andrea Pezzuolo, Francesco Marinello, Luigi Sartori and Stefano Guercini	
Comparison of Environmental Impact of Two Different Bioelectricity Conversion Technologies by Means of LCA	619
Mauro Villarini, Sara Rajabi Hamedani, Vera Marcantonio, Andrea Colantoni, Massimo Cecchini and Danilo Monarca	

Ergonomics and Work Organization

Spatial Analysis for Detecting Recent Work Accidents in Agriculture in Italy 631

Massimo Cecchini, Ilaria Zambon, Danilo Monarca, Francesca Piccioni, Alvaro Marucci and Andrea Colantoni

A Bottom-Up Approach to Tractor Safety: Improving the Handling of Foldable Roll-Over Protective Structures (FROPS) Through User-Centred Design 645

Lucia Vigoroso, Federica Caffaro, Margherita Micheletti Cremasco, Ambra Giustetto, Giuseppe Paletto and Eugenio Cavallo

Technical and Economic Evaluation of Urban Trees Pruning by Climbing Arborists 653

M. Biocca, P. Gallo and G. Sperandio

First Tests on a Prototype Device for the Active Control of Whole-Body Vibrations on Agricultural Tractors 661

Daniele Pochi, Laura Fornaciari, Renato Grilli, Monica Betto, Stefano Benigni and Roberto Fanigliulo

Effects of Rod and Oscillating Frequency on the Vibrations Transmitted to Hand-Arm System by Four Olive Portable Harvesters 671

Giuseppe Manetto, Emanuele Cerruto and Rita Papa

Perceived Barriers to the Adoption of Smart Farming Technologies in Piedmont Region, Northwestern Italy: The Role of User and Farm Variables 681

Federica Caffaro and Eugenio Cavallo

Effect of Different Axial Fans Configurations on Airflow Rate 691

S. Failla, E. Romano, D. Longo, C. Bisaglia and G. Schillaci

Machines and Plants for Processing Agricultural Production

Use of Ultrasound in the Extraction Process of Virgin Olive Oil and Influence on Malaxation Time 703

Mauro Pagano, Roberto Tomasone, Carla Cedrola, Marco Fedrizzi, Gianluca Veneziani and Maurizio Servili

An Innovative Vat for the Continuous Recovery of Volatile Compounds During Fermentation 713

Giulia Angeloni, Lorenzo Guerrini, Piernicola Masella, Agnese Spadi, Fabio Baldi and Alessandro Parenti

Effect of Packaging Technology on the Quality of Pre-cooled Clementine Fruit	723
F. Genovese, G. C. Di Renzo, G. Altieri, L. Scarano and M. C. Strano	
Optimization of Donkey Milk Pasteurization Process	735
A. Matera, G. Altieri, F. Genovese and G. C. Di Renzo	
Effect of Materials and Assembly Methods on Gas Selectivity of Blow[®] Device	745
A. Matera, G. Altieri, F. Genovese and G. C. Di Renzo	
Information and Communication Technologies	
Monitoring of Coffee Tree Growth Through Crop Surface Models and MGRVI with Images Obtained with RPA	757
Gabriel Araújo e Silva Ferraz, Luana Mendes dos Santos, Marco Thulio Andrade, Leticia Aparecida Gonçalves Xavier, Diogo Tubertini Maciel, Patricia Ferreira Ponciano Ferraz, Giuseppe Rossi and Matteo Barbari	
A Prototype of Service Oriented Architecture for Precision Agriculture	765
S. Lanucara, A. Oggioni, S. Di Fazio and G. Modica	
A Method to Implement a Monitoring System Based on Low-Cost Sensors for Micro-environmental Conditions Monitoring in Greenhouses	775
Elio Romano, Massimo Brambilla, Pietro Toscano and Carlo Bisaglia	
An Innovative Methodology to Be More Time-Efficient When Analyzing Data in Precision Viticulture	783
Monica F. Rinaldi, Raimondo Gallo, Gabriele Daglio and Fabrizio Mazzetto	
AgroBot Smash a Robotic Platform for the Sustainable Precision Agriculture	793
D. Sarri, S. Lombardo, R. Lisci, V. De Pascale and M. Vieri	
Use of a Multicopter-UAV Equipped with a Multispectral Camera to Detect Vineyard Diseases: A Case Study on Barbera and Dolcetto Cultivars	803
Gabriele Daglio, Raimondo Gallo, Monica F. Rinaldi, Nadia Massa, Valeria Todeschini and Fabrizio Mazzetto	
An Ontology-Based Study for the Design of a Database for Data Management in Precision Farming	811
S. Chiappini, A. Galli, E. S. Malinverni, P. Zingaretti, R. Orsini, M. Fiorentini and S. Zenobi	

A Skyline Deflection Analysis Methodology for Timber Volume Estimation in Yarding Operations	819
Raimondo Gallo, Luca Marchi, Stefano Grigolato, Raffaele Cavalli and Fabrizio Mazzetto	
Neural Network Algorithms for Real Time Plant Diseases Detection Using UAVs	827
Mariano Crimaldi, Vincenzo Cristiano, Angela De Vivo, Marco Isernia, Plamen Ivanov and Fabrizio Sarghini	
Use of UAVs and Canopy Height Model Applied on a Time Scale in the Vineyard	837
Luca Ghiani, Alberto Sassu, Vanessa Lozano, Giuseppe Brundu, Davide Piccirilli and Filippo Gambella	
Development of a Matlab Code for the Evaluation of Spray Distribution with Water-Sensitive Paper	845
Luca Ghiani, Alberto Sassu, Davide Piccirilli, Gian Luca Marcialis and Filippo Gambella	
Detection and Monitoring of Alien Weeds Using Unmanned Aerial Vehicle in Agricultural Systems in Sardinia (Italy)	855
Vanessa Lozano, Giuseppe Brundu, Luca Ghiani, Davide Piccirilli, Alberto Sassu, Maria Teresa Tiloca, Luigi Ledda and Filippo Gambella	
Experimental Methodology for Prescription Maps of Variable Rate Nitrogenous Fertilizers on Cereal Crops	863
Costanza Fiorentino, A. R. Donvito, P. D'Antonio and S. Lopinto	
Monitoring Onion Crops Using UAV Multispectral and Thermal Imagery: Preliminary Results	873
Gaetano Messina, Salvatore Praticò, Biagio Siciliani, Antonio Curcio, Salvatore Di Fazio and Giuseppe Modica	

Assessment of Forest Biomass and Carbon Stocks at Stand Level Using Site-Specific Primary Data to Support Forest Management



Luca Nonini, Calogero Schillaci and Marco Fiala

Abstract To quantify and map woody biomass (WB) and forest carbon (C) stocks, several models were developed. They differ in terms of scale of application, details related to the input data required and outputs provided. Local Authorities, such as Mountain Communities, can be supported in sustainable forest planning and management by providing specific models in which the reference unit is the same as the one reported in the Forest Management Plans (FMP), i.e. the forest stand. In the Lombardy Region (Northern Italy), a few studies were performed to assess WB and forest C stocks, and they were generally based on data coming from regional—or national—forest inventories and remote sensing, without taking into account data collected in the FMPs. For this study, the first version of the stand-level model “WOody biomass and Carbon ASsessment” (WOCAS) for WB and C stocks calculation was improved into a second version (WOCAS v2) and preliminary results about its first application to 2019 forest stands of Valle Camonica District (Lombardy Region) are presented. Since the model WOCAS uses the growing stock as the main driver for the calculation, it can be applied in any other forest area where the same input data are available.

Keywords Forest modelling · Woody biomass · Carbon stock · Forest management plan · Site-specific primary data · Climate change mitigation

1 Introduction

Forests provide several Ecosystem Services (ES), commonly classified as: (i) regulating, (ii) provisioning and (iii) cultural (Costanza et al. 1997; Bennett et al. 2009; Krieger 2011). The quantification of the demand (human society) and the supply (environment) of ESs is a key challenge to define the effective environmental management practices and to identify the best institutional scale for the decision-making

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processes (Daily and Matson 2008; Swetnam et al. 2011; Kroll et al. 2012; Marchetti et al. 2012; Garcia-Gonzalo et al. 2015). In the context of the current climate change scenario, the most important forest ESs are: (i) woody biomass (WB) supply and (ii) carbon (C) stock (Nabuurs et al. 2008; Ekholm 2016; Gren and Zeleke 2016). WB supply and C stock are indicators of provisioning and regulating services, respectively, and they are competing, as an increase in WB supply generally causes a reduction of C stock in the forest (Bottalico et al. 2016). To quantify and map these two ESs, several models were developed; they differ in terms of scale of application (single tree, whole stand, regional or continental level), details related to the input data required and outputs provided (Vanclay 1994; Pretzsch et al. 2009; Klein et al. 2013; Pilli et al. 2013). In the alpine forestry region, Mountain Communities are the main Local Authorities having a key role in forest planning and management (Cantiani 2012). At this purpose, stand-level models are particularly important because stands represent the reference unit of the Forest Management Plans (FMP). FMPs make available a wide range of primary (measured) data that can be used to estimate the current WB (and the corresponding aboveground and belowground C stock), the harvested mass and their variation over time. In the Lombardy Region (Northern Italy) only a few studies were performed to assess WB and forest C stocks, and they were generally based on data coming from regional—or national—forest inventories and remote sensing (Federici et al. 2008; Colombo et al. 2009). None of these studies took into account primary data collected in the FMPs. Considering all these elements, the aims of this study were: (i) to develop a model—based on site-specific primary data—to calculate WB and C stocks at the stand level, (ii) to test the model for the Valle Camonica District (Lombardy Region) and (iii) to map the spatial distribution of these stocks at different levels (from the stand, to the municipality and to the whole forest area under assessment).

2 Materials and Methods

2.1 *The Model WOCAS*

A first version of an empirical stand-level model called “WOody biomass and Carbon ASsessment” (WOCAS) was developed to calculate the annual WB and C stocks in different forest pools. This model was recently improved into a second version (WOCAS v2) by: (i) adding new information (FMPs new data), (ii) defining more accurate calculation methods and (iii) improving the general structure to increase the model’s reliability and flexibility. For a generic (j) forest stand, for the year n, calculations are performed in the following pools: (i) aboveground woody biomass ($AWB_{n(j)}$), (ii) belowground woody biomass ($BWB_{n(j)}$) and (iii) dead organic matter ($DOM_{n(j)}$; dead woody biomass + litter) by applying a mass balance based on a “gain-loss” approach consistent with the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006; Federici et al. 2008).

For each of the j -stand, the input data required are: (i) starting ($YR_{S(j)}$) and final ($YR_{F(j)}$) year of the FMP, (ii) forest typology, (iii) forest function (e.g. production, environmental protection, recreational), (iv) forest structure (i.e. coppice, high forest), (v) area ($A_{(j)}$; ha), (vi) growing stock at $YR_{S(j)}$ ($GS_{(j)}$; t year⁻¹ dry matter, hereafter DM) and (vii) harvested growing stock over time ($H_{n(j)}$; t year⁻¹ DM).

For each harvesting operation, the corresponding woody residues ($HR_{n(j)}$; t year⁻¹ DM)—consisting in tree stumps, tops, branches, twigs and non-commercial parts—are also calculated (IPCC 2006). Woody residues represent a loss from the living $AWB_{n(j)}$ and $BWB_{n(j)}$ pools, and—if they are left on the ground and are not extracted from the stand—a gain for the $DOM_{n(j)}$ pool.

For the year n , starting from the growing stock of the previous year ($GS_{n-1(j)}$; t year⁻¹ DM), the gross annual increment ($GAI_{n(j)}$; t year⁻¹ DM) is calculated by applying the first derivative of the Richards growth function (Richards 1959; Pienaar and Turnbull 1973; Birch 1999; Federici et al. 2008). Then, the net annual increment ($NAI_{n(j)}$; t year⁻¹ DM)—defined as $GAI_{n(j)}$ minus growing stock losses within the same period of time due to natural mortality (UNECE/FAO 2011)—is quantified.

Two types of natural mortality are considered: (i) regular (RM), due to senescence, competition for light, water, nutrient and from the normal incidence of pests, diseases, and weather phenomena, and (ii) irregular (IM), due to wildfires, windstorms, avalanches, insect outbreaks or other disturbances (Vanclay 1994; Alenius et al. 2003). Regarding the former, the model assumes that the growing stock losses ($GS_{RMn(j)}$; t year⁻¹ DM) occur each year, whereas, regarding the latter, information about: (i) year of occurrence, (ii) type of disturbance and (iii) growing stock losses ($GS_{IMn(j)}$; t year⁻¹ DM) has to be defined by the user. As well as for the woody residues, natural mortality represents a loss from the living $AWB_{n(j)}$ and $BWB_{n(j)}$ pools, and a gain for the $DOM_{n(j)}$ pool. In more detail, for the regular mortality, the model assumes that all the $GS_{RMn(j)}$ are transferred to the $DOM_{n(j)}$ pool, whereas, for the irregular mortality, the model calculates the fraction of the $GS_{IMn(j)}$ transferred to the $DOM_{n(j)}$ pool according to the type of disturbance.

The growing stock in the year n ($GS_{n(j)}$; t year⁻¹ DM) is then calculated starting from the $GS_{n-1(j)}$ (t year⁻¹ DM), adding the $NAI_{n(j)}$ (t year⁻¹ DM) and subtracting losses due to the harvested growing stock, $H_{n(j)}$ (t year⁻¹ DM). The living $AWB_{n(j)}$ and $BWB_{n(j)}$ (t year⁻¹ DM) stocks are calculated by multiplying the $GS_{n(j)}$ for specific coefficients (Somogyi et al. 2007; Federici et al. 2008) defined according to the stand's characteristics.

The $DOM_{n(j)}$ in the year n is calculated by taking into account, as inputs: (i) $GS_{RMn(j)}$, (ii) $GS_{IMn(j)}$ and (iii) $HR_{n(j)}$, and as output, the $DOM_{n(j)}$ decomposition, by using specific decay rates (Harmon et al. 1986; Melin et al. 2009) defined according to the stand's characteristics.

Finally, the carbon stocks in: (i) $AWB_{n(j)}$ ($C_{AWBn(j)}$, t year⁻¹ C), (ii) $BWB_{n(j)}$ ($C_{BWBn(j)}$, t year⁻¹ C) and (iii) $DOM_{n(j)}$ ($C_{DOMn(j)}$, t year⁻¹ C) are calculated by multiplying the WB of each pool for the corresponding carbon fraction, k_C ($k_{C_AWB(j)}$;

$k_{C_BWB(j)}$; $k_{C_DOM(j)}$). The sum of: (i) $C_{AWBn(j)}$, (ii) $C_{BWBn(j)}$ and (iii) $C_{DOMn(j)}$ allows to calculate the total carbon content of the j -stand.

2.2 Case Study

The model WOCAS was applied to the Valle Camonica District to estimate WB and C stocks of the public forests. The total forest area is equal to 6.5×10^4 ha (52% of the total area); the public forests (managed through FMPs) cover 4.2×10^4 ha, whereas the private forests (not managed through FMPs) cover the remaining 2.3×10^4 ha. Among the coniferous, the main species are *Picea abies* L. and *Larix decidua* Mill. (30% and 20%, respectively), whereas, among the broadleaves, the main species are *Alnus viridis chaix* D.C. and *Castanea sativa* Mill. (11% and 8%, respectively). Production forests cover about 60% of the total forest area, followed by protection and recreational forests (38% and 2%, respectively).

For the study, data related to 2019 forest stands (forest area equal to 3.7×10^4 ha, approximately) were extracted from 45 FMPs collected in the Cadastral FMPs database (CPA v2) made available by the Mountain Community. The dataset covered the period from 1984 (starting year of the oldest FMP) to 2016 (no more recent data were made available from the CPA v2).

To calculate the gross annual increment, specific growth parameters were used for each of the j -stand, according to species and type of management (Vitullo 2018); these parameters were made available by the Italian Institute for Environmental Protection and Research (ISPRA) and represent the ones used for the official UNFCCC National Inventory Report (NIR) for Land Use, Land Use Change and Forestry (LULUCF) sector for the Lombardy Region. The $GS_{RMn(j)}$ ($t \text{ year}^{-1} \text{ DM}$) were assumed equal to 9.25% of the $GAI_{n(j)}$ (Tabacchi et al. 2010; Magnani and Raddi 2014). As a preliminary assessment, no differences among the stands were introduced. The $GS_{IMn(j)}$ ($t \text{ year}^{-1} \text{ DM}$) were not considered because no data were made available from the CPA v2. To calculate the $HR_{n(j)}$ ($t \text{ year}^{-1} \text{ DM}$), as well as the $AWB_{n(j)}$ and the $BWB_{n(j)}$ ($t \text{ year}^{-1} \text{ DM}$), the coefficients suggested by Federici et al. (2008) for the Italian forests were used. To simulate the $DOM_{n(j)}$ decomposition, not having specific data related to the Italian forests, the values of decay rates suggested by Harmon et al. (2001) for temperate forests were applied. Specific values of $k_{C_AWB(j)}$ were considered, by taking into account the stem of the leading species (Thomas and Martin 2012). Moreover, it was assumed that $k_{C_AWB(j)} = k_{C_BWB(j)} = k_{C_DOM(j)}$.

3 Results and Discussion

The main results of the last 2 years of the analysis (2015 and 2016)—for which the data of all the stands were made available from the CPA v2—are shown in Table 1.

Table 1 WB and forest C stocks related to the 2019 stands considered in the case study

		Unit	Year	
			2015	2016
Harvested growing stock	H_n	t year ⁻¹ DM	1.5×10^4	4.1×10^3
Gross annual increment	GAI_n	t year ⁻¹ DM	8.6×10^4	8.6×10^4
Net annual increment	NAI_n	t year ⁻¹ DM	7.8×10^4	7.8×10^4
Growing stock	GS_n	t year ⁻¹ DM	3.1×10^6	3.2×10^6
Aboveground woody biomass	AWB_n	t year ⁻¹ DM	4.1×10^6	4.2×10^6
Carbon stock in the aboveground woody biomass	C_{AWB_n}	t year ⁻¹ C	2.0×10^6	2.1×10^6
Belowground woody biomass	BWB_n	t year ⁻¹ DM	9.0×10^5	9.2×10^5
Carbon stock in the belowground woody biomass	C_{BWB_n}	t year ⁻¹ C	4.4×10^5	4.5×10^5

For both the year 2015 and 2016, the harvested growing stock (H_{2015} and H_{2016} , respectively) is lower than the net annual increment (NAI_{2015} and NAI_{2016} , respectively) ($H_{2015} = 19.2\% NAI_{2015}$; $H_{2016} = 5.3\% NAI_{2016}$). The ratio between H_n and NAI_n represents the effective extraction rate ($EER \geq 0$) and is one of the most important indicators for the sustainable forest management. In fact, if in the short term H_n can exceed NAI_n ($EER > 1$), i.e. for years characterized by a high demand of woody biomass (for energy and/or building purposes), in the medium-long term this condition should never occur ($EER \leq 1$), to avoid the depletion of the growing stock over time and of the stand's productivity (UNECE/FAO 2011; Magnani and Raddi 2014). The EER values can be calculated with a higher accuracy by taking into account also the irregular mortality (disturbances), that strongly affects the NAI_n of the stands. Therefore, it is recommended to improve the data collection in the CPA v2 by including information about the natural disturbances. H_n , if performed in compliance with the sustainable forest management indicators, should be considered as a positive event because, besides allowing the rational use of an economically exploitable local resource, can promote a further increase of the annual increment and—as consequence—of the carbon sequestration. As a result, the homeostatic capacity of the forests can be enhanced, promoting a higher resistance to natural disturbances. The results provided by this study also show that the belowground woody biomass, generally not taken into account by the FMPs, is an important carbon pool, because it can stock about 22% of the total carbon of the aboveground biomass. These results can be obtained for each stand under analysis, single municipality, species, forest structure or function, making it possible to carry out a great deal of analysis and comparisons.

By integrating the model WOCAS with a Geographic Information System (ArcGIS®) a stand classification worksheet (SCW) was produced for each of the j-stand.

Each SCW provides two kinds of information (K_1 and K_2). K_1 contains general input information extracted from the CPA v2 (e.g. location, stands' owner); K_2 contains specific input (e.g. growing stock at the starting year of the FMP, harvested growing stock over time, forest typology, type of management) and output (calculated by the model) data, as well as information related to the mechanization (type of cutting performed and forestry machines that can be used according to the site-specific working conditions).

4 Conclusions

The use of management models able to calculate WB and forest C stocks is essential to analyze the contribution of these lands to climate change mitigation. In the alpine regions, the use of stand-level models based on data collected in the FMPs could be an interesting solution if the use of single-tree level models clashes with the technical-economic impossibility of the Local Authorities to provide the data required. In this study, the empirical stand-level model WOCAS was briefly presented and the main results about its application to a dataset of 2019 forest stands of Valle Camonica District were discussed. The main advantage of this model is that—besides being based on the international 2006 IPCC Guidelines—it uses the growing stock (generally available in any FMP) as the main driver for the calculation; as a result, it can be applied in any other forest area where the same input data are collected. Two aspects are currently under development: the first one concerns the definition of different management scenarios to quantify the masses of the woody assortments (and their carbon stock) that can be extracted from each stand and used for building and/or energy purposes. This aspect is very important, also considering that the commitments of the recent post-2012 agreements of the Kyoto Protocol include not only the need to report carbon emissions and removals related to forest management, but also the carbon stock in the harvested woody products. The second aspect consists in the definition of future scenarios based on both current and improved forest management practices (i.e. conversion of coppices to high forests) to test the model under different temporal and spatial scales and management conditions. In this way, it will be possible to make predictions and formulate prescriptions promoting an efficient use of the local forestry resources.

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