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Review Article

Research and innovation in agriculture: beyond productivity?

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Abstract. Studies on the effects of research and innovation in agriculture have been largely characterised by efforts to make a connection between expenditure and productivity. A number of issues have challenged the ability of productivity to measure the effects of research, namely, in recent years, increasing efforts towards improving the environmental performance of the farming sector. Besides environmental concerns, however, a number of recent concepts have emerged that are shaping the current research and policy agenda and which could result in a revision of the productivity concepts used to evaluate research impacts. The objective of this paper is to discuss these issues and their implications for studies on the impact of research and innovation. We address, in particular, the following issues: a) the development of the of bioeconomy and related concepts such as the circular economy, resource efficiency and bio-refinery; b) the connection with entrepreneurship and eco-innovation; c) changing tools in research assessment, in particular the widespread use of Life Cycle Assessment (LCA); and d) the evolving concepts of sustainability and ecosystem services. We argue that while the traditional notion of productivity, intended as output/input ratio, maintains (and may be strengthens) its role on the aggregate, a more analytical interpretation of the pathways towards research impacts is needed, as well as a broadened view of productivity and its determinants.

Keywords. Agriculture, research, innovation, productivity, bio-refinery, circular economy, bioeconomy

JEL Codes. Q16

1. Introduction and objectives

The link between research, innovation and productivity has gained growing attention in the last decade. The productive focus of agriculture in the mid-twentieth century appeared rather straightforward. Yet the environmental crisis of the late twentieth century brought a wider variety of issues to the forefront. At the outset of the twenty-first cen-

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tury, the dilemma in EU agriculture appeared to be whether to move towards more traditional, organic farming or to modern biotechnology-based agriculture (De Wilt *et al.*, 2001). Now, however, the scenario is more complex. On the one hand, different agricultural technologies and sustainability pathways co-exist (worldwide at least); on the other hand, attention has moved from choosing between existing technologies to a focus on new technological developments through innovation. At the same time, the concept of sustainability is changing: initially it was focused mainly on environmental effects, then enlarged to economic and social sustainability and resource efficiency. The recent decade has refocused attention on feeding the word while preserving resources for future generations, which is the "mantra" of the current debate and recent events (see EXPO 2015), with a clear renewed attention on productivity.

Policy has followed and promoted this change in focus. An example is the evolution of the Common Agricultural Policy (CAP) from providing incentives to production through market support, to focusing more on income support, to a mix of sustainability and income support, and to the present aggregate of productivity, resource efficiency and climate change concerns.

The relationship between research, innovation and productivity has taken on a growing policy focus in the EU (in particular with the EU2020 strategy), with an increasing focus on competitiveness, innovation and resource efficiency. This has also affected subsequent policy implementation, including the CAP 2014-2020. In this programming period, and in particular in the rural development component, innovation has a prominent role, including new connections with research, especially through the new instrument represented by the European Innovation Partnership (EIP).

The focus of agricultural research in the last two centuries has followed the needs expressed by society and policy, with deep changes over time (Spierz, 2014). In recent years, increasing attention to public good production by agriculture (environmental, working quality etc.) has affected both the focus of research and the breadth of impacts that would be necessary to measure to account for these effects.

A general definition of productivity is the ability of production factors to produce output (Latruffe, 2010). This can be measured through a ratio between output and input. However, a wide body of literature has treated productivity measures in agriculture addressing both conceptual and practical issues in implementing this concept. The literature includes simple measures of partial productivity (e.g. relating output to individual inputs as well as measures accounting for more than one input (e.g. multiple factor productivity). A more comprehensive measure of productivity is Total Factor Productivity (TFP), which is a ratio of the (monetary) aggregation of all outputs and the aggregation of all inputs. This concept often follows a time series approach to account for productivity improvements based on changes in TFP (Coelli, 2005; Latruffe, 2010). Fuglie (2015) shows that TFP has a major role in accounting for the growth of agricultural production over time, though with a differing weight in different time periods and in different regions. Productivity indexes have been discussed and extended to account for a number of issues, including the growing variety of inputs and outputs related to environmental and resources concerns. Several multi-output, resource-saving, or dynamic specifications are now attempting to tackle these issues. This has led, among others, to proposing extensions such as environmentally adjusted TFP or even green TFP (e.g. Chen and Golley, 2014).

Besides measuring productivity, the economic literature has attempted to investigate the factors affecting productivity and its changes. This has been done largely through econometric models using productivity measures as dependent variables and various influencing factors as explanatory variables. Among such factors, research and innovation have a prominent role. In particular, the research to date has focused on seeking to make a connection between research expenditure and productivity (Alston *et al.*, 2010, 2011; Wang *et al.*, 2013). Research and innovation are indeed potentially key explanatory variables of changes in productivity over time. Through the provision of new knowledge (increasing the knowledge stock), embedding this knowledge in new technologies (enlarging the technology set) and the diffusion of innovation in the economic system, research is expected to directly affect the relationship between input and output and hence improve productivity. In this way, the role of research and innovation can be seen as a way of escaping (or at least modifying) trade-offs among goods, given limited resource availability, by enhancing technical possibilities. Yet as research is costly, this implies a trade-off between present consumption and investment in technology development.

Methods used to assess this connection may utilise econometric techniques on large data sets of (relatively simplified) information, as well as case study type approaches (Alston *et al.*, 1995; Gaunand *et al.*, 2015). Altogether, the link between research, innovation and productivity is conceptually straightforward, but much less easy to streamline in practice. This is partly due to technical issues, such the practical difficulties in proving numerically the linkage between research and productivity change, in part due to data limitations. Further conceptual difficulties are due to the complexity of the system connecting research, innovation and productivity. This is underscored by, among others, the long-standing debate about the difficulty in matching demand and supply of innovation, the on-going discussion regarding the functioning of knowledge and innovation systems, and the growing discussion on the multiple directions (functions and objectives) of agriculture and related research. There are also potential counterintuitive effects of research, such as the negative impacts of highly codified public research on local enterprises (Maietta, 2015).

Making this linkage has also become more difficult over time due to the increased variety of technology pathways (conventional, integrated, organic and more) used in agriculture and of the goods (private, public, intermediate) produced by agriculture. These issues have been exacerbated in recent years by the emerging focus on the bioeconomy and renewed attention devoted to resource efficiency and productivity. The concepts related to the bioeconomy emphasise the complexity of technical and economic linkages that can transmit the effects of research (Viaggi *et al.*, 2012; Swinnen and Weersink, 2013). Finally, worldwide trends, including the opening of various economies and climate change, have given additional weight to uncertainty and dynamics, with a special emphasis on non-linear and "non-trend" dynamics and fundamental uncertainty in the outcome and relevance of any technology change and policy action.

It is now rather well established that the assessment of the impacts of research (especially public research) should deal with multiple dimensions, covering not only economic, but also environmental, health, social, and policy impacts. Furthermore, it is accepted that innovation results from the activities and interactions of multiple actors. Understanding the impact of a research activity/organisation increasingly requires paying attention to the intermediaries as well as the beneficiaries (i.e. the innovation network) of the research results (Gaunand *et al.*, 2015).

While some of the issues above have already been covered extensively in the literature, others are rather new and the scientific community is still in the process of identifying the challenges ahead.

The objective of this paper is to discuss the link between research, innovation and productivity in agriculture in light of selected emerging economic and sustainability concepts, mainly, but not exclusively, linked to the development of the bioeconomy.

The paper addresses, in particular, the following issues in relation to the link between research and productivity: a) the concept of 'bioeconomy' and related concepts such as the circular economy, resource efficiency and bio-refinery; b) the connection with entrepreneurship and eco-innovation; c) changing tools in research assessment, in particular the widespread use of Life Cycle Assessment (LCA); and d) the evolving concepts of sustainability and ecosystem services.

In relation to these fields, this paper attempts to identify implications for the concept of productivity and for the understanding of the linkage between research and productivity, in particular seeking to identify developments that may challenge the current notion of productivity. This reasoning is then used to develop implications for future research. The paper does not intend to focus specifically on the measurement of productivity (though this is clearly an important issue in this context and is implicitly or explicitly addressed at several points in the paper). Rather, it focuses on the connection between objectives/mechanisms and the effects of research.

Moreover, while recognising that the issue has relevance for all scales of analysis, the focus of this paper is implicitly more on the micro to meso level and closer to the research level, compared with many productivity-oriented studies. In addition, it tends to be more on the threshold between decision support and assessment methods, largely because the paper seeks significant inspiration from trends in evaluation practice and decision making concerning research and innovation funding.

We do not restrict attention to a specific field of research; while at the same time not excluding research in the social sciences, however, the paper focuses more on "classical" technological research.

The paper is organised in three main sections beyond this one. In the next Section (2), we review the literature on the four issues listed above and their implications for tracing the effects of research on productivity; in Section 3 we discuss the implications of the findings from the literature for future research and evaluation practices. Concluding remarks are provided in Section 4.

2. Research and productivity: selected issues

2.1 Changing paradigms in economic organisation: bioeconomy, circular economies and bio-refinery

The concept of the bioeconomy, based on the sustainable exploitation of biological resources, has emerged as a key strategy in many countries to meet human needs while taking into account resource efficiency requirements. After having proposed several different definitions in recent years, the EU Communication on the Bioeconomy and the accompanying working document (European Commission, 2012a; European Commission, 2012b) defines the bioeconomy as encompassing "the production of renewable biological resources and their conversion into food, feed, bio-based products and bioenergy. It includes agriculture, forestry, fisheries, food and pulp and paper production, as well as parts of chemical, biotechnological and energy industries. Its sectors have a strong innovation potential due to their use of a wide range of sciences (life sciences, agronomy, ecology, food science and social sciences), enabling and industrial technologies (biotechnology, nanotechnology, information and communication technologies (ICT), and engineering), and local and tacit knowledge."

Based on this delimitation, the EU bioeconomy accounts for an annual turnover of more than 2 billion euro (of which almost half from the food sector) and more than 20 million employees. Besides its economic importance and potential, the bioeconomy strategy provides major challenges for policy and research. Several of these challenges are already taken up in the work programmes of the Seventh Framework programme and the Horizon 2020 research and innovation program of the EU.

The definition of the term 'bioeconomy' is still a matter of discussion (see Schmidt *et al.*, 2012), in part due to the fact that different countries have been using different definitions. For example, the OECD and the USA definitions are more focused on biotechnology than that of the EU. Different views are also linked to the use of the term bioeconomy in different branches of research, with different normative visions of technology. In particular, there is an emerging tension between an industrial/process vision of the bioeconomy and a territorial/landscape vision. In spite of this diversity, a common feature of the different visions of the bioeconomy is the central role of knowledge, research and innovation.

From the point of view of tracing the impact of research, the bioeconomy goes in the direction of making the problem more "analytical" and more difficult. First, it tends to promote a stronger decomposition of material flows, and increasing the potential for re-combinations. In addition, it tends to promote cross-discipline and cross-sector "contaminations", making it more difficult to identify the flows of effects. Finally, working with biological materials tends to increase the degree of uncertainty about the characteristics of input and output, as well as of the outcome of research processes and their applications.

A final and perhaps more important issue is that, given the knowledge-based nature of the bioeconomy, the impact of research critically depends on the stock of available knowledge and how it is mobilised to exploit newly produced knowledge.

A symptom of the complexity and difficulty in providing clear-cut judgements is that the development of the bioeconomy is accompanied by a mix of opposite expectations about its effects and its role in ensuring sustainability. Pfau *et al.* (2014) identify different visions: (1) the assumption that sustainability is an inherent characteristic of the bioeconomy; (2) the expectation of benefits under certain conditions; (3) tentative criticisms in light of potential pitfalls; and (4) the assumption that the bioeconomy impacts negatively on sustainability. This clearly hints at the potential opposite (ambiguous) effects of the bioeconomy on sustainability.

A concept largely embedded in the bioeconomy discourse is that of bio-refinery. Biorefinery is the sustainable processing of biomass into a spectrum of bio-based products and bioenergy. It is based on the idea of a stepwise treatment of biomass starting from the highest added-value components down to energy (cascading approach) in such a way as to make the most out of limited biomass resource availability. Bio-refinery in Europe is promoted as one of the key economic organisational concept in the bioeconomy, in particular for non-food chains.

The research may focus on different issues in this field. One key focus is the extraction of an increasing number of products from the same initial biomass; however, the qualifying feature of bio-refinery is the ordering of extraction, in such a way as to maximise the value of production prior to the destruction of the biomass. This also goes in the direction of a higher level of disaggregation of biomass in more simple and basic components that can later be used as the building blocks of a variety of products. The degree of pureness of the obtained materials seems to have an added value here. At the same time, in many cases, the actual value of such products is uncertain due to the fact that they are "far" from final products, new to the market (or new substitutes of existing ones) or due to quality issues (presence of residues etc.). Moreover, technologies developed by new research may yield a displacement of effects from one step to the other or change the structure of downstream processes after changing a step in the process. Finally, research can also lead to modified economic relationships, e.g. new products may have the potential to transform by-products into main products, justifying the process based on market forces, with implications in the allocation of effects. This effect is potentially more important as the number of potential extractions from the same raw material grows. As in all processes using biomass, which are often characterised by high transport costs per unit, spatial location is an essential feature of industrial organisation and the economic viability of processes.

An emerging concept closely connected to the bioeconomy is that of the circular economy, which relates to the idea that the economy should rely less on external raw materials and more on the re-use of resources that are already in the system. Chertow and Ehrenfeld (2012) define the circular economy and discuss the process of the organisation of circular economies in industrial symbioses.

At present, the circularity of the economy (measured by the degree of circularity intended as the share of materials that flow back into the antropic system) is rather limited. Hass *et al.* (2015) provide an estimation of the degree of circularity of the global and the EU-27 economy for 2005. They show that there is a global flow of roughly 4 gigatonnes per year (Gt/yr) of recycled waste materials; this is of moderate size compared to 62 Gt/yr of processed materials and 41 Gt/yr of outputs. Biomass has an important role in this process as it accounts for 19 Gt/yr with only a 3% (7% in the EU-27) degree of circularity. One of the reasons for this is that biomass is largely used for energy purposes (including food), which makes it non-recyclable.

Here, however, the definitions and the system considered are of significant importance; if biomass is produced sustainably (that is, without damaging soil or water resources and without depleting ecological carbon stocks), it can be considered renewable and the emitted CO_2 as well as waste flows can largely be recycled into new primary biomass within ecological cycles (Jordan *et al.*, 2007).

Closing the cycle for biomass-related industries hence involves closing the cycle of nutrients (nitrogen and phosphorous), reducing waste from production and consumption, changing dietary patterns towards less meat demanding diets. As a result, both agriculture and food are heavily affected by the process of getting to a more circular economy, or, looking at the other side of the coin, can directly contribute to it.

The concept of the circular economy has implications not only in terms of the organisation of the economy, but also in relation to the role of technologies and, hence, research. Indeed, a growing focus of research is now related to closing the cycles of key materials, e.g. nutrients. This implies considering the degree of closeness of an economy as a key indicator of performance of the system or a change thereof as an important impact indicator for research. At the same time, the focus on circularity questions traditional productivity measures if they do not qualify the origin of raw materials (recycled or newly extracted).

In economic terms, this implies investigating the different economic values attached to external versus re-used resources. Resources are re-used at a cost; external resources have a cost affected by extraction costs and scarcity rents. Both costs may change depending on the quantity allocated to a given source or another. This hints at least at the idea that the degree of closeness of an economy may not tell the full story in economic terms, as actual values may be not proportional to the degree of closeness/openness. Instead, the value of resources in classical productivity measures can actually be more informative about the degree of optimal closeness of an economy, except in the case of externalities, market distortions or information failures. When market prices are not considered to be good estimates, shadow price approaches may help to investigate the actual degree of scarcity of resources (e.g. Halvorsen and Smith, 1984).

Finally, an issue related to impacts in the circular economy and bioeconomy (i.e. using living organisms) is that scarce resources may in fact change over time, depending on the availability of resource stocks and technology. A pertinent example is the growing attention to the increasing scarcity of phosphorous in the field of agriculture. Hence, eventual indicators of circularity may require the flexibility to change over time to account for critical issues. Another issue that is typical of living organisms is their inherent variability, which should be taken into account in both evaluation and policy design (Carillo e Maietta, 2014).

2.2 Entrepreneurship and eco-innovation

The role of the different actors in research and innovation is another issue that is changing dramatically. In a simplified (older) vision of research and technology uptake, the market and policies played major roles. The market was seen as a promoter of private research and the main determinant of technology uptake, whereas the public sector, for its part, was a research provider and promoter of targeted technology uptake, e.g. through subsidies. The transfer of innovation from science to the industry, initially thought of as a sort of linear process, has been over time supported by specific extension policies aimed at smoothing and encouraging this one-way flow.

This naive idea of technology transfer has been widely challenged over time, notably by investigating the number of actors, institutions and mechanisms that provide a bridge between research and the farming sector and considering feedback loops between the farming sector and research. The broad-based literature on Agricultural Knowledge and Innovation Systems (AKIS) indicates that this has become increasingly important in agriculture, especially in relation to the bioeconomy (Esposti, 2012). Relevant categories go beyond single extension units and farmers. Networks are becoming a more and more important category in this field. Networks also support a dynamic view of the innovation process, in which different types of actors can get involved at different stages and innovators need to continuously reflect and re-position themselves with respect to their environment. This view of the innovation process also implies that facilitators and innovation monitoring and evaluation methods can play a major role. In addition, it implies a rethinking of policies to ensure that they are not excessively aimed at determining innovation direction, but rather support facilitation activities and the emergence of innovation initiatives (Klerkx *et al.*, 2010). Accounting for higher and growing complexity also requires adequate approaches for research and evaluation. A pertinent example is that of the impact pathways evaluation approach (Douthwaite *et al.*, 2003).

Participatory approaches in different steps of the research to innovation processes have become particularly evident in the context of EU initiatives. The process started with the EU Technology platforms at the outset of the Seventh Framework Programme and has become paramount in the context of the new Horizon 2020 programme, focusing on the contribution to competitiveness through research and innovation and promoting a multi-actor approach in research projects.

In this context, one of the most relevant phenomena in recent decades, which was also largely supported by the development of the bioeconomy, is the role of entrepreneurship in research and innovation. Entrepreneurship can take different forms, from brokerage of innovation as a specific business activity, to the financing of innovation, up to a sort of "innovation entrepreneurship". Moreover, the process of developing 'entrepreneurship' activities and attitudes by researchers is increasingly being promoted. The role of entrepreneurship has attracted attention in the field of biotechnology for at least two decades with the emergence of the term "bio-entrepreneurship" (Schoemaker and Schoemaker, 1998). The concept includes a wide range of typologies, ranging from researchers developing enterprises to exploit their knowledge to entrepreneurs investing in life science research and development companies. This concept is now widespread and increasingly used in specific educational programmes involving university students and researchers (see e.g. Uctu and Jafta, 2015).

This pathway also draws attention to the process of building research objectives and priorities. A specific point concerns the growing role of businesses in building innovation strategies and, through these, guiding the development of oriented applied research. As this approach becomes more important, the building of circular connections between research and business seems to be giving additional weight to business, which is providing a vision for the future, while research has more and more the (limited) aim of buttressing this vision with much needed knowledge.

From the point of view of impact evaluation, a key issue in recent years is the incorporation of collective values (e.g. public goods concerns such as environmental and resource issues) into market strategies by the private sector. This can be viewed as the progressive merging of private and public type values. This is witnessed by a process of strategic choice on the part of industry, awareness and related behavioural changes by consumers and the appropriate functioning of markets and marketing, including the communication of values and the transmission of information about products and processes.

In the incorporation of 'green' concerns into private business, a key concept is that of eco-efficiency. The concept attempts to reconcile economics and the environment. The

World Business Council for Sustainable Development (WBCSD) in 1992 defined eco-efficiency as being " …achieved by the delivery of competitively-priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the earth's estimated carrying capacity" (Schmidheiny, 1992, cited in Govindan *et al.*, 2014).

The green economy has been put forward as an even more positive and environmentally focused way of seeing the economy. It is intended as an economy seeking to reduce environmental and ecological impacts and that fosters sustainable development without degrading the environment. It also incorporates the idea of fairness.

An interesting area of attention linking research and the green economy is provided by eco-innovation, which also offers examples of the articulated interplay between firm strategies, their economic context and inter-firm relationships. The exploration of the factors of eco-innovation effort is considered to be at the heart of new research directions in the new millennium (Rashid *et al.*, 2014), driven in particular by four eco-innovation drivers: regulatory push, technology push, market pull, and firm strategies. In the context of this trend, the connection between vision, research objectives and the impacts of technological innovation is becoming of central importance. For example, Björkdahl and Linder (2014) explain how and why a shared environmental vision can accelerate environmental innovation. Specifically, they emphasize that a shared environmental vision can lead to an increase in the number of application areas and in increased market sales based on existing green solutions. However, they also show that the efficacy of the shared vision is dependent on a good match between the environmental problems faced and the core competencies of the firm.

Cuerva *et al.*, 2014 found that the factors driving eco-innovation are different from other types of innovations. Based on a questionnaire carried out in the Spanish Food and Beverage sector, they found that technological capabilities such as R&D and human capital foster conventional innovation, but not green innovation. On the contrary, the implementation of Quality Management Systems (QMS) and differentiation contribute only to the adoption of green innovations. One of the findings of this study is that greater implementation of voluntary certification schemes would be more effective in enhancing eco-innovation than public subsidies. Furthermore, attention to collaboration and the needs of consumers are positively associated with eco-innovation. Triguero *et al.* (2013), studying eco-innovation in Europe at the firm level, found that those entrepreneurs who give importance to collaboration with research institutes, agencies and universities, and to the increase in market demand for green products, are more active in all types of eco-innovation. Greater attention to existing regulations shape eco-product and eco-organisational innovations while expected regulations and access to subsidies and fiscal incentives do not have any significant effect on decisions to eco-innovate.

Policy, management and communication instruments are playing a key role here as promoters of change. For example, quality management and certification schemes have been at the core of a wide field of research in recent decades and are increasingly the subject of analysis. New communication technologies may have a key role in boosting these connections, e.g. by improving the awareness of consumers and their ability to choose, or providing information, for example, about the quality and eco-friendliness of products. Examples include apps that help search for non-GMO, organic, or in-season food[1]. The role of these technologies in shaping awareness, preferences and future demand-supply interaction is still largely unexplored.

2.3 Emerging methods for measuring the impacts of research: towards a diffuse life cycle assessment approach?

Another strategy for understanding the implications of current trends in the analysis of the links between research and productivity is to look at instruments for measuring the impacts of (new) technologies and, indirectly, of research. In this perspective, a dominant role is currently played by Life-cycle assessment (LCA). LCA is an assessment method focusing on impacts generated by each unit of product (or, more appropriately, functional unit) along its lifecycle, from "cradle to grave". The basis of the method is a compilation of the inventory of inputs and outputs, notably with reference to key resources (e.g. energy, water) or pollutants (e.g. GHG, nitrogen).

Besides the inventory phase, LCA is being expanded to include the evaluation of differences among technology alternatives, including the use of multi-criteria analysis and the linkage with economic performance, e.g. using lifecycle costing, along the life cycle of a given product.

LCA has been used for more than two decades as an environmental assessment tool and is increasingly used to support marketing messages. It is increasingly used as the basis for the selection of products in 'green procurement' and the inclusion of products in various national and regional eco-labelling schemes, i.e. European Flower, German Blue Angel, Nordic Swan eco-label etc. It is now widely promoted for early evaluation of research and innovation processes. In particular, LCA was already applied in the Seventh Framework programme of the EU (Tilche and Galatola, 2008) and is now regularly required in the calls of Horizon 2020.

In principle, LCA responds to the basic idea of productivity, though expressed in a reverse way, i.e. aiming at minimising the unit of input and emission per unit of product. Notably, however, it tends to maintain a multidimensional and rather broad (and diverse) view of such a ratio, depending on the environmental indicators measured for input and output.

From the point of view of the linkage between research and productivity, LCA addresses the need to better account for the broader impacts of technological research, hence considering a potentially wide range of effects on complex systems. In addition, it seeks to account for environmental effects along the value chain of a given product (broken down in different key phases), hence being able to explicitly account for displacement or compensatory effects at different stages of the chain. It also takes into consideration by-products and recycling. Furthermore, LCA makes it possible to support prescriptions regarding the steps in the process where intervention/research is more urgent due to higher criticalities in terms of impacts.

For its characteristics, LCA appears especially suitable to address the impacts of innovation and research applied to the emerging issues discussed above (bioeconomy, circular

[1] http://grist.org/list/this-powerful-app-brings-organic-farming-into-the-candy-crush-age/
http://foodtank.com/news/2013/10/twenty-three-mobile-apps-changing-the-food-system

economy and bio-refinery). In fact, several papers already report applications referred to these issues. For example, Mattila et al (2012) discuss the methodological aspects of applying LCA to industrial symbioses and, more generally, to circular economies. The literature is also developing on the specificities of the application of LCA to bio-refinery systems (Sandin *et al.*, 2015).

LCA is also at the forefront of the measurement of eco-efficiency, which to date has been using different methods, ranging from simple indicators to modelling. LCA and DEA are arguably amongst the most used (Govindan *et al.*, 2014; Lin *et al.*, 2012). An example of the application in agriculture is available in Picazo-Tadeo *et al.* (2012).

Yet LCA applications have also experienced difficulties and the above-referenced literature emphasise a number of open issues. While databases are now more and more available for standard applications of well-established technologies, coefficients needed for new technologies or for rapidly evolving product chains are often not readily available. Conceptual issues related to the boundaries of the system remain open, especially for not yet well-structured or evolving production chains. Moreover, LCA yields comparable results only when the functional unit is perfectly comparable, which weakens the potential for comparing different products or processes yielding different results in terms of services. Applications to the concepts of bioeconomy and biorefinery emphasise the issue of the attribution of impacts internally to the system considered; at the same time, as the process is purposely designed to yield multiple products, the issue of finding a common functional unit or to allocate common effects to different products is also highlighted. Sandin *et al.* (2015) explore how the choice of the allocation methods influences results and in which decision contexts the choice is particularly important, by testing six allocation methods in a case study of a bio-refinery using pulpwood as feedstock. The results indicate that the choice of allocation method deserves careful attention, particularly in consequential studies and in studies focussed on co-products representing relatively small flows.

An issue of specific interest for this paper is that LCA tends to focus attention on environmental/resource use, whilst economic and social impacts remain more difficult to account for. Notably, recent attention has been devoted to the use of Life Cycle Costing (LCC), which is an economic assessment tool considering all projected significant and relevant cost flows over a period of analysis expressed in monetary value. It can be applied to a physical asset life or to the life cycle of a product/services in analogy to LCA. Notably, this is gaining attention for use in public procurement, another area of innovation in which the purchasing power of public institutions is used to provide incentives towards environmentally friendly technologies (IISD, 2009; Dragos and Neamtu, 2013).

From an economic point of view, two key nodes remain open issues, in particular in evaluating the impact of research. First, the way in which research can impact the production process includes several variables (e.g. uptake, organisation of the production process, concentration etc.), which makes it necessary to estimate potential impacts based on a number of assumptions. The use of LCA and location (including related limitations) must also be considered in the light of the different types of chains addressed: i.e. short, long, and global. Concepts connecting the measurement of impacts and trade relationships are also emerging, such as virtual water and water footprint.

Second, the "engineeristic" impact in terms of changes in flows needs to be given an economic value. This also implies assumptions about, for example, the location of impacts.

Taking the case of the use of water resources, abstraction can have unit costs of a different order of magnitude depending on the source used. It should also be acknowledged that the distribution of impacts across sectors can be non-neutral.

An issue related to the economics of LCA information is its role in decision-making. On this issue, Sandin *et al.* (2014) note that, "particularly in inter-organisational R&D projects, the roles of LCAs tend to be unclear and arbitrary, and as a consequence, LCA work is not adequately designed for the needs of the project considered. There is a need for research on how to choose an appropriate role for LCA in such projects and how to plan LCA work accordingly" (Sandin *et al.*, 2014, p. 97). Similarly, considering the connection with the work on the measurement of eco-efficiency, Govindan *et al.* (2014), draw attention to the need to better connect these studies to supply chain management.

2.4 From performance to positioning: sustainability and ecosystem services

The wider context in which the above issues have been developed has been characterised by the widespread use of the concept of sustainability as the increasingly important aim of agriculture and food systems and, related to that, of sustainability-oriented technology change.

Without entering into the debate with respect to the definition of sustainability, it is clear from the literature that it is to a large extent related to socially constructed notions. On the one hand, the literature points out and advocates the need for the political process to define sustainability (Schepers, 2014). On the other hand, it is claimed that sustainability is a continuous social learning path and that such a transformation should be "profound (e.g. affecting moral standards and value systems), transversal (e.g. requiring the involvement of individuals as well as collective action) and counter-hegemonic (e.g. requiring the exposure and questioning of stubborn routines)" (Wals e Rodela, 2014).

It is also important to emphasise that the problems encountered are not only related to providing adequate definitions, but also touch upon the empirical conceptualisation and practical measurement of sustainability, including its relationship with globalisation and development literature (Olson *et al.*, 2014).

A good example of the practical problems faced in the measurement of sustainability is given by the approaches towards the assessment of environmental sustainability of agriculture, somehow the component of sustainability better studied, as compared to economic and social sustainability. This issue has been largely addressed in the literature through the use of indicators (Bockstaller *et al.*, 2008). As the number of indicators developed is both high and varied, the literature has also formulated a number of proposals for composite indicators and integrated sustainability assessments (Rodrigues *et al.*, 2010a; 2010b). Moreover, a number of methodologies have been developed relying not only on more or less complex (sets of) indicators (Singh *et al.*, 2009), but also on modelling (Ness *et al.*, 2007).

The literature notes the contradiction among the different requirements expressed towards these tools, which are expected to be at the same time specific yet broad, tailored but standardised (Ness *et al.*, 2007). There is also demand for composite indexes, whilst recognising that simple aggregate indexes can provide misleading information to decision-makers (Singh *et al.*, 2009). In most cases, data availability remains the clearest criterion for decisions about the individual indicators and tools to be used. Bockstaller *et al.* (2008)

conclude that, as the data available at the regional level are usually limited, several simple indicators should be used, at least at this level. Only when more detailed information is available can indicators based on operational models be useful. In experimental studies, when possible, it is suggested to use both measured indicators and model-based indicators.

In recent years, concepts such as resilience and vulnerability have increasingly accompanied or replaced that of sustainability. The detailed consideration of each of these terms would require the examination of a wide body of literature, which is beyond the scope of this paper. Notably, all of these issues have found noteworthy parallel use in ecology, environmental economics and development economics, highlighting the importance of dynamics and the relevance of "potential" effects/changes. Another feature of these concepts is their attempt to be comprehensive, which is at times pursued at the cost of difficulties with accurate definitions and measurement.

The most direct implication for productivity measures arising from this field of study is a push for a stronger consideration of sustainability in both output and resource concerns. It should, however, be emphasised that expectations regarding easy corrections of traditional productivity measures may be overambitious. One of the consequences of the increasing uncertainty in the different interpretations of 'sustainability' and the difficulty in the measurement of outcomes/impacts of processes, accompanied by the quest for more comprehensive concepts, is the move towards proxies able to measure the positioning towards the future, rather than the direct measurement of outcomes/impacts either *ex-ante* or *ex-post*. As a consequence, also in relation to the measurement of productivity and of the effects of research, the consideration of proxies, or of a limited number of selected issues (most likely measuring pressures), could remain the more realistic option.

A concept closely related to sustainability assessment is that of Ecosystem Services (ES). According to TEEB (2010), ES are the direct and indirect contributions of ecosystems to human well-being. They are most often categorized into four types (MEA, 2003; TEEB, 2010): provisioning, regulating, habitat and cultural services. In contrast to other approaches, the ES approach takes ecosystems directly into account and links them to the uses that human beings can make of the services they provide. The approach has gained a broad consensus and has increasingly been adopted in policymaking. The use of ES presents several advantages, among which, notably for the scope of this paper, to include in the same framework services directly linked to "traditional" productivity measures (provisioning) and those that relate to other ecosystem roles in human life, thus making explicit the various trade-offs, synergies and relative weights. On the other hand, ES make it possible to link issues related to the economics of sustainability with the ecosystem context and to cast sustainability issues in a territorial and landscape dimension (van Zanten *et al.*, 2014). Of significant importance is also the fact that the concept seems to be particularly suitable for policy communication.

On the other hand, a number of studies show that the understanding of ES, and their inherent trade-offs, require an enlargement of the system considered and hence re-introduces, and even emphasises, the trade-offs between detail and comprehensiveness. Furthermore, ES does not solve data issues, which remain a key driver of the choice of specific indicators and their measurement strategies, nor do they address the problem related to the attribution of economic values to ES services, at least for the part represented by public goods-type services and externalities (Viaggi, 2015).

Another issue linked to sustainability is related to the strategies currently being used to achieve improved product sustainability. Far from traditional end-of-pipe approaches, current strategies directly address process and product design, value chain organisation or even producer habits. This is the focus of a wide body of literature on alternative technology options in agriculture, but it is now also of increasing importance for food production. In this regard, van der Goot *et al.* (2016) list several technological strategies, including: avoiding dilution, minimizing drying, focusing ingredient production on functionality rather than purity, tailoring ingredient production to specific applications rather than for general use, developing smaller and more flexible fractionation processes which should also be located in the vicinity of the application, and using milder process conditions for less refined ingredients. In other words, sustainability concerns are increasingly embedded in the whole product design and chain/system functioning.

Similar approaches are advocated for most of the issues connected to sustainability, including the promotion of the circularity of the economy. These considerations have implications in particular for the measurement of impact in research aimed at improving sustainability, which in fact tends to require an analysis (and awareness) of entire processes and a comprehensive view of the related economic dimensions.

3. Discussion, implications for research and the way forward

Each of the issues and perspectives illustrated above has potential specific implications for the relationship between research, innovation and productivity and for the measurement/evaluation of the impacts of research.

The implications can be broadly organised into three interconnected topics:

a) measurement of productivity;
b) parameters able to explain changes in productivity, especially due to research;
c) ways of making the connection between research efforts and productivity change.

As far as the measurement of productivity is concerned (point a) the emergence of environmental and resource problems, and the new areas of concern illustrated above, have primarily brought to the attention (even more strongly than before) the need to expand the range of output indicators and the range of resources to be considered as input. Besides this, the current trends seem to introduce novelties in the quality of the effects sought, which are increasingly represented by: a) soft effects, amenable to interpretations and flexibility in the social construction of related values (and hence prices), and; b) effects that are more valued for their potential than for their actual observable effects.

Altogether, while the classical measures of productivity remain key references at the aggregate level, the emerging attention to circular economies and resource efficiency brings into question, in particular, the application at intermediate and lower levels of aggregation (chains, firms, small territorial units). Here, the widespread diffusion of LCA signals (and partially responds to) the need to develop more functional measures of the effects of (and in) different steps in the chain, and brings directly to attention the technological and economic inter-linkages among different processes. LCA is itself, however, challenged by the emphasis on circularity and by the social construction of values related to impacts. Indeed, the discrepancy between more accurate technical measures of impact (or at least pressures) and the limited ability to valuate their effects in economic terms is still very high. It is likely that the new issues emerging from the development of the bio-economy will further contribute to this discrepancy, making the effects of research even more difficult to measure objectively.

These reflections also lead to question the extent to which economics can actually play a role in measuring productivity effects in light of current technological development. On the one hand, many issues addressed above, such as circularity in the economy, can already be incorporated into the measures currently being used, if prices work well, particularly with respect to scarcity. On the other hand, it is becoming more difficult to account monetarily for the preferences of final consumers, who are becoming less stable and more driven by perceptions, expectations and information distortions (especially for services that are less and less related to basic needs or for those that are new for consumers). It is also becoming difficult to identify the economic mechanisms that are determining the impact of research, starting with the use of new knowledge and the adoption of new technologies.

In this context, the traditionally clear distinction between private and public goods and the category of externalities (and the related instruments for economic valuation), are also weakening due to the "marketization" of environmental and social values, the increasingly explicit socially (or policy) driven construction of values and preferences and the growing number of cases of goods that are somewhere between private and public. These trends expose the system to the instability of preferences over time, which may lead to difficulties in prediction, overlapping and double counting. They also require (and partially ensure) greater attention to information and communication, the embedding of technology change in participatory processes, and the awareness of the processes leading to the construction of values.

Similarly to output measurement, the interpretation and understanding of determinants of productivity (point b), and among them research, also require effort to account for an increasing number of parameters that contribute to the explanation of productivity changes. This includes accounting better for a larger number and diversified quality of input, more complex interplays among sectors and larger geographical interactions. A specific element requiring attention is the strengthening of the connection between research and innovation efforts and the stronger linkages with human capital and entrepreneurship attitudes.

Changes in the way research is performed must also be better analysed. Research is becoming increasingly analytical, cross sector and taking on multiple methods of interaction (in interdisciplinary, multidisciplinary and transdisciplinary contexts). It is also necessary to take into account the multiple number of actors, which also imply different ways of understanding the directions of interaction among different pieces of knowledge. In this framework, information about research expenditure, even when available, becomes less and less satisfactory in accounting for research efforts, without considering the increasing difficulties in linking expenditures to the specific objectives of research (and hence expectations about the direction of its impacts).

Furthermore, specific attention should be paid to understanding how to account for the existing stock of knowledge. Past research expenditure is less and less a good way for accounting for the increased stock of very diversified knowledge; this issue in itself deserves to be the subject of more focused research, considering improved proxies and a better understanding of mechanisms taking into account spatial dynamics, including flows of knowledge and technology.

The connection between research and its effects (point c), is possibly the most puzzling of the three topics listed above, and its evolution is still less studied compared with performance measurement and its potential determinants. In addition, recent literature shows that addressing this link is not only a matter of measuring items, but more widely of understanding and codifying cause-effect relationships among factors affecting the direct and feed-back loops between research, technology adoption and performance change.

Relevant issues to be accounted for include scope and scale of the evaluation, i.e. what is the right bundle of products/issues to be addressed and at what geographical level and process detail. Bioeconomy research is a good example of the need to better understand how to address these issues: innovation tends to be increasingly analytical in improving processes as its effects are becoming "finer" and there is a tendency toward a greater disaggregation of biomass into smaller blocks. But some concerns do exist (among which sustainability, counteracting this trend). The joint pathway of the circular economy and biorefinery is leading towards the need for more analytical and more comprehensive approaches. Yet their effects and, arguably, the perception of their effects has become more ambiguous and difficult to measure.

A more specific issue relates to time lags for the effects of research. Most of the literature emphasises that long time lags are necessary to allow research to impact on productivity (Alston, 2010; Wang, 2013). However, the evolution of the bioeconomy and the explicit focus on innovation in research programmes (see Horizon, 2020) may be expected to push for reducing such lags, or, more likely, to diversify even more the lags among the various pieces of research. This variety of potential time lags is also visible from having a simultaneous quest for very applied research supporting short-term innovation and a very open "blue sky" (in the words of the EU Commission) and fundamental research. In addition, given the status of continuous change and the different technologies that interact, the role of both indirect and unexpected effects, which may in fact occur at different points in time, are more prominent.

Another economic issue, stemming in part from the evolution in governance/legislation and the existence of more sophisticated technologies, is the growing complexity of property rights in research results. This makes the use of research results and the appropriation of their benefits more distributed, while the participation in the exploitation and the potential for alternative uses of knowledge also become wider whilst, at the same time, requiring more flexible ways of collaboration.

Given this complexity of chain effects, one of the strategies for future understanding of the impact of research would be to look at shorter chains of effects, i.e. between research and adoption/organisation, or between adoption and performance, rather than trying to address the long way between research and final changes in the system, with the related causality problems.

Altogether, one could argue that, while the productivity of research should remain and even become a more important focus of research, the real priority issue is not the measurement of impacts (though it is to some extent), but rather the mechanisms making the link between research and its impacts, which could also be considered as a good (or the best) proxy of impact itself, or at least as a measure of potential impact.

Several pathways for further research crosscutting the simplified three points illustrated above can be identified. These include, notably, the following:

1. There is a need to identify improved representations of goods, technologies and their change that can be used to better account for the current trends in technologies that break down biomass and recombine its compounds; one direction could be in representing input as bundles of attributes (elements) and the output as potential attributes rather than products.
2. There is also a need to better investigate new institutional mechanisms, especially the role of entrepreneurship in research, knowledge exploitation and the social construction of successful technologies. This connects with the notion of business models and the "shape" (or, better, "non-shape") of enterprises (which, metaphorically, can be better represented by an amoeba rather than any other constant form concept) becoming more and more a bundle of loosely connected rights and values; this trend is emphasised by the growing complexity in technology ownership and the exploitation of innovation.
3. A better study of the interplay between consumers and producers, beyond simplified market mechanisms, is also needed. On this issue, new awareness building and marketing strategies (social networks) and thoroughly informed/aware communities (yet often limited in their intepretation ability) connecting demand and supply, boosted by new technologies (e.g. smartphones) call for the need for collaboration and linkages between studies on production and studies on consumption in order to directly deal with uncertainty about prices and market shares. This is particularly relevant for new technologies for which the market has yet to be developed, in which frequently changing or new policy measures are also often observed.
4. New communication technologies have a key role in several of the processes mentioned above; though they are playing a disruptive role in changing societies, their role as means and promoters of change in economic behaviour linked to innovation and exploitation of research is still insufficiently studied.
5. There is also a need for studies on tools and strategies to deal with uncertain futures. A specific issue related to emerging technologies and their interplay with awareness and market building is the difficulty in predicting futures; trends are less and less a relevant indication for the future, while a breakthrough of new solutions may be more relevant. On this point, economic valuations using potential trend-breaking scenarios may require greater attention with respect to on past-based expectations.
6. The investigation of new potential tools to measure productivity and link with research is also needed. The existing tools are for the most part well-established in the literature; sometimes they are seen to be novel when "discovered" by different disciplinary fields or when new variants become available, but in the last couple of decades there have mostly been incremental innovations rather than radical innovations in this field. Contamination among existing tools could be a promising pathway and is already under way, e.g. studies proposing combinations of LCA and DEA analysis, or LCA and Multi-criteria analysis.
7. This goes hand by hand with the further development of studies to better understand research and technology impact pathways in this changing context; a distinguishing feature of future studies could be found in a more extended use of impact

pathways approaches, to better account for the larger set of determinants discussed in this paper.

8. An investigation into the new role of policy and related mechanisms is also needed. Not only regulation and policy-defined prices contribute to reveal and signal preferences through the value chain; the building of new markets is becoming a stronger policy issue that has a broad range of implications. Indirect policy mechanisms, such as those helping to reveal preferences related to public goods or facilitating coordination, are becoming more important, yet continue to be poorly understood. An increased emphasis on policy measures related to awareness, information, education and knowledge management may also result in the need for different tools to study policies, e.g. more qualitative and systemic tools.
9. Information and data needs remain a key issue for researchers in the field of the evaluation of research impacts on productivity. Gaps primarily involve productivity measures, in particular "non-conventional" components of productivity, such as environmental improvements considered in multi-output productivity specifications or input-saving approaches. Data gaps are also very much relevant for research expenditure and potential intermediate explanatory variables (e.g. AKIS actors). However, it should be emphasised that this issue cannot be restricted to complaints regarding insufficient data availability. Rather, data users and providers should collaborate in co-construct data sources taking into account forward looking needs. In addition, greater attention should be given to emerging sources of data due to the digitalisation of huge amounts of information and related opportunities for data mining and linkages of databases (still largely unexploited).

4. Conclusions

This paper has investigated the implications for research, innovation and productivity studies of selected bioeconomy-related issues, namely: a) the concepts of bioeconomy, circular economy, resource efficiency and bio-refinery; b) the connection with entrepreneurship and eco-innovation; c) changing tools in research assessment, in particular the widespread use of LCA; and d) the evolving concepts of sustainability and ecosystem services.

We argue that the "traditional" idea of productivity intended as an output/input ratio maintains (and may strengthen) its role on the aggregate, though the current trends in research are more focused than they were in the past on creating "potential" rather than straightforward changes. Furthermore, we find that, while the role of research in productivity change is likely increasing, it is becoming somewhat more difficult to link changes in productivity to specific research actions.

As a result of the above, the understanding of the interconnections and pathways between research and productivity are becoming more relevant than final productivity measures themselves, though much more difficult to trace than in the past.

Policy and practitioners are requiring improved ways of performing *ex-ante* and *ex-post* analyses that are better connected with decision making and capable of managing interplays between aggregate and disaggregate levels. This is also in line with a growing emphasis on incorporating sustainability concerns into private (both firm and consumer) behaviour while dealing with globalised markets and global environmental and social concerns.

This highlights a number of new challenges for research in economics, especially related to agriculture, food and the bioeconomy. A key issue concerns the need for methodological developments, which may find their basis in the improved knowledge of new research processes and new technologies, as well as in a better understanding of surrounding societal change. It also requires economists to take up the "procedural" and cultural challenges of an increased involvement in the agriculture and bioeconomy innovation system, while at the same time guaranteeing objective analyses and robust independent judgements, suitable for evidence-based support to decision-making.

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