

ENABLING CROP DIVERSIFICATION TO SUPPORT TRANSITIONS TOWARD MORE SUSTAINABLE EUROPEAN AGRIFOOD SYSTEMS

Antoine MESSÉAN (✉)¹, Loïc VIGUIER¹, Lise PARESYS¹, Jean-Noël AUBERTOT², Stefano CANALI³, Pietro IANNETTA⁴, Eric JUSTES⁵, Alison KARLEY⁴, Beatrix KEILLOR⁴, Laura KEMPER⁶, Frédéric MUEL⁷, Barbara PANCINO⁸, Didier STILMANT⁹, Christine WATSON¹⁰, Helga WILLER⁶, Raúl ZORNOZA¹¹

1 French National Institute for Agriculture, Food and Environment (INRAE), Eco-Innov, F-78850 Thiverval-Grignon, France.

2 French National Institute for Agriculture, Food and Environment (INRAE), UMR AGIR, Toulouse, France.

3 Council for Agricultural Research and Economics-Research Centre for Agriculture and Environment (CREA-AA), 00184 Rome, Italy.

4 The James Hutton Institute, Invergowrie, Dundee, DD2 5DA, UK.

5 French Agricultural Research Centre for International Development (CIRAD), Persyst Department, F-34398 Montpellier, France.

6 Research Institute of Organic Agriculture (FiBL), 5070 Frick, Switzerland.

7 Terres Inovia, F-78850 Thiverval-Grignon, France.

8 University of Tuscia, Department of Economics, Engineering, Society and Business Organization, 01100 Viterbo, Italy.

9 Wallon Agricultural Research Centre (CRA-W), Sustainability, systems and perspectives Department, B-6800 Libramont, Belgium.

10 Scotland's Rural College (SRUC), Craibstone Estate, Aberdeen AB21 9YA, UK.

11 Technical University of Cartagena, Department of Agricultural Engineering, Cartagena, Spain.

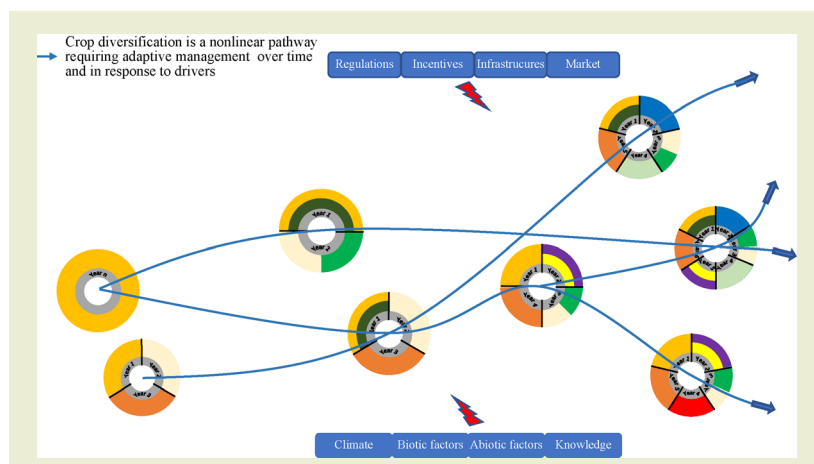
KEYWORDS

crop rotation, lock-in, intercropping, multiple cropping, networking

HIGHLIGHTS

- Crop diversification is a dynamic pathway towards sustainable agrifood systems.
- Technological and institutional barriers restrict uptake of crop diversification.
- More coordination and cooperation among agrifood system stakeholders is required.
- The European Crop Diversification Cluster calls for multiactor networks.

GRAPHICAL ABSTRACT



ABSTRACT

European cropping systems are often characterized by short rotations or even monocropping, leading to environmental issues such as soil degradation, water eutrophication, and air pollution including greenhouse gas emissions, that contribute to climate change and biodiversity loss. The use of diversification practices (i.e., intercropping, multiple cropping including cover cropping and rotation extension), may help enhance agrobiodiversity and deliver ecosystem

Received January 26, 2021;

Accepted May 17, 2021.

Correspondence: antoine.messean@inrae.fr

services while developing new value chains. Despite its benefits, crop diversification is hindered by various technical, organizational, and institutional barriers along value chains (input industries, farms, trading and processing industries, retailers, and consumers) and within sociotechnical systems (policy, research, education, regulation and advisory). Six EU-funded research projects have joined forces to boost crop diversification by creating the European Crop Diversification Cluster (CDC). This Cluster aggregates research, innovation, commercial and citizen-focused partnerships to identify and remove barriers across the agrifood system and thus enables the uptake of diversification measures by all European value-chain stakeholders. The CDC will produce a typology of barriers, develop tools to accompany actors in their transition, harmonize the use of multicriteria assessment indicators, prepare policy recommendations and pave the way for a long-term network on crop diversification.

© The Author(s) 2021. Published by Higher Education Press. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0>)

1 INTRODUCTION

Over the past few decades, European agriculture has focused on the production of only a very small number of crop species (the so-called major crops) with the objective of increasing the economic efficiency of agrifood systems, leading to a sharp decline in within-field and landscape crop diversity^[1]. These agrifood systems are reliant on the overuse of external inputs (i.e., synthetic fertilizers and pesticides) leading to strong adverse impacts on the environment such as soil degradation, water eutrophication and air pollution including greenhouse gas emissions that contribute to climate change and biodiversity erosion (e.g., soil microbes, birds and insects)^[2–8]. Currently, low diversity cropping systems (i.e., monocropping and short rotations) and associated global and long value chains dominate European agrifood systems, leading to unsustainable food- and feed-production^[9].

A transition of European agriculture from the current external input dependent cropping systems to biodiversity-based or ecologically-based ones relying more on ecosystem services, along with the development of local and short value chains, is a major path to face the challenges of balancing production with environmental preservation^[10].

Crop diversification is one of the levers that can contribute to increasing within-field biodiversity which supports ecosystem services and helps to close nutrient cycles allowing to substitute for chemical inputs as well as supporting more diversified agrifood systems at large.

2 WHAT IS CROP DIVERSIFICATION?

Crop diversification is the act or process of diversifying crop production including annual and perennial crops for food, feed, bioenergy, and green and white industrial uses. Crop diversification practices include higher heterogeneity within species and the way they are grown in spatial and temporal scales (Fig. 1):

- (1) In proximity within the same land area (e.g., row intercropping, strip intercropping, mixed cropping, relay intercropping and agroforestry);
- (2) On the same land area within a growing season (multiple cropping including cover crops during fallow periods); and
- (3) On the same land area in successive growing seasons (crop rotation).

Crop diversification can also include higher heterogeneity within crop cultivars (i.e., genetic diversification) and/or mixture of cultivars^[11].

Crops introduced in diversified cropping systems are:

- (1) Major cash crops, i.e., crops with large volumes of production in Europe (e.g., oilseed rape), benefiting from important investments from agrifood system stakeholders (e.g., genetic improvements or steady market outlets);

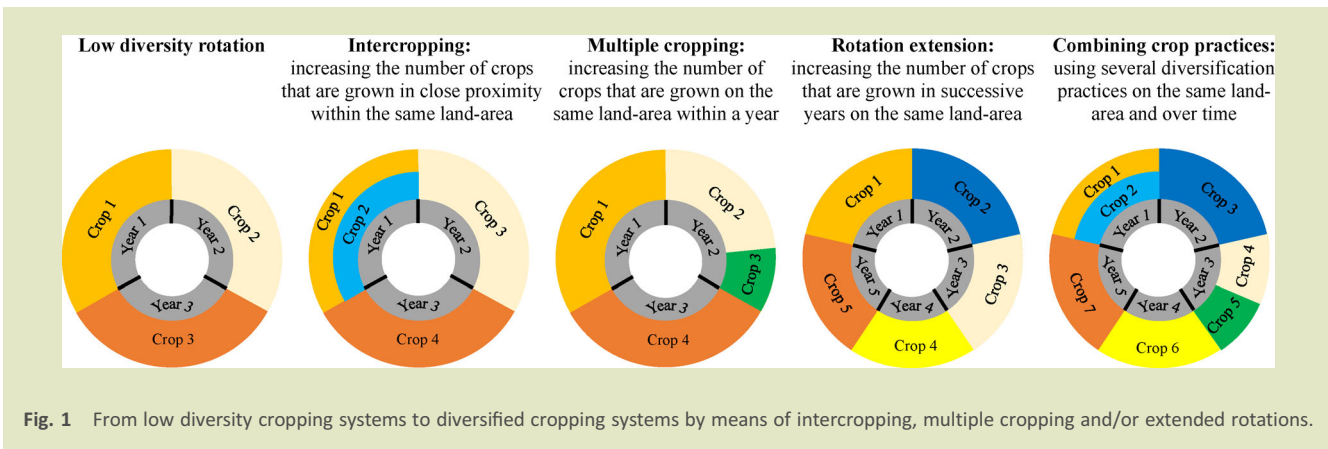


Fig. 1 From low diversity cropping systems to diversified cropping systems by means of intercropping, multiple cropping and/or extended rotations.

(2) Minor cash crops, i.e., crops with relatively low volumes of production in Europe (e.g., lentil, pea), that have received relatively low investments from agrifood system stakeholders; and

(3) Multiservice cover crops, i.e., crops that are grown to provide specific ecosystem services (e.g., biomass production, dinitrogen fixation, soil erosion prevention, and disease or pest suppression).

Making smart use of the potential benefits of crop diversification may secure the production of agricultural products for food, feed, bioenergy and industrial uses, allowing food and nutrition security^[12] while reducing the use of chemical fertilizers and pesticides. Overall, crop diversification may increase resilience to environmental changes through income diversification, restored biodiversity and soil quality^[13].

Crop diversification is not an objective *per se*, but a means to redesign the current agrifood systems toward greater economic and environmental sustainability^[14].

3 WHY IS THE POTENTIAL OF CROP DIVERSIFICATION LOCKED-IN FOR FARMERS AND THE AGRIFOOD SYSTEM?

Actors of the European agrifood systems have coevolved toward the production and use of major crops creating highly-organized long value chains resulting in an important sociotechnological lock-in of agrifood systems and a strong interdependency between its actors^[9,15,16].

Farmers willing to adopt crop diversification lack technical

knowledge, adapted equipment and locally-adapted minor crop varieties, mainly due to lower research investments from public institutions and private companies. Beyond farmers, value-chain actors face relatively high transaction costs (e.g., collection and storage) because of low, unstable production volumes and scattered supplies of minor crops compared to highly-structured value chains. Also, downstream value-chain actors find difficulties in making the benefits of crop diversification visible enough that consumers are willing to pay price premiums for the products of diversification practices^[16]. Finally, public regulations do not provide incentives for crop diversification as policies are still very much centered on major crops and their associated long value chains^[17]. This unfavorable socioeconomic context often renders minor crops less competitive than major crops, especially in a globalized commodity market^[15,18].

The importance of these barriers has been strengthened in time as the dominant agrifood systems have benefited from massive investments from all stakeholders. This has resulted in a strong interdependency of agrifood system actors toward low diversity systems, hindering the implementation and the support of diversification practices^[9].

4 CROP DIVERSIFICATION IS A DYNAMIC AND NONLINEAR PATHWAY TOWARD SUSTAINABLE AGRIFOOD SYSTEMS

Farmers who attempt to diversify their cropping systems face numerous environmental, climatic and socioeconomic challenges which require adaptive management of their cropping systems to limit trade-offs between economic, social and environmental performance^[19,20]. Also, diversified cropping systems produce a large range of crops requiring adapted value

chains and coordination with other actors of the agrifood system. This dynamic and nonlinear pathway to crop diversification requires all actors to continuously adapt their practices in a coordinated manner over time^[16]. There is no one-size-fits-all solution, i.e., a range of diversification practices should be developed to address the diversity of local soil, climatic and socioeconomic conditions across Europe.

5 WHAT IS THE EUROPEAN CROP DIVERSIFICATION CLUSTER DOING?

In 2017, the European Commission launched six new projects related to crop diversification (Table 1).

- (1) **DIVERSify** and **ReMIX** focus on optimizing intercropping for more sustainable cropping systems;
- (2) **TRUE** and **LegValue** promote wider use of legumes which are often minor crops although key candidates to support diversification because of the ecosystem services they can provide; and
- (3) **Diverfarming** and **DiverIMPACTS**, whose scope is broader than the other projects and includes multiple cropping and rotation extension in addition to intercropping as well as addressing how value chains should be reorganized.

Overall, the Crop Diversification Cluster (CDC) gathers more than 120 actors and operates in 21 countries across Europe and internationally to increase the impact of crop diversification research and support scientific progress and actions enhancing diversification measures by European farmers and through innovations across the agrifood system.

The CDC has set up five working groups of partners from across the Cluster projects to boost collaborations within projects and to strengthen the outputs on the following topics (Fig. 2):

- (1) Identifying barriers to crop diversification and solutions to overcome them;
- (2) Designing innovative cropping methods, decision tools and new resources to support crop diversification;
- (3) Developing indicators and multicriteria approaches for assessment of performance at the field, farm, value chain and landscape levels;
- (4) Elaborating policy recommendations to facilitate the implementation of crop diversification practices; and
- (5) Disseminating outputs of the Cluster working groups, communicating joint activities and forging international collaborations.

6 WHAT WILL BE THE MAIN OUTPUTS OF THE CROP DIVERSIFICATION CLUSTER?

The outputs of the CDC will be diverse in nature (e.g., experimental data, stakeholder networks and policy recommendations) and concern the whole agrifood system. Outputs come from the transversal work within the Cluster working groups and from the projects. Here is a list of the main expected outputs:

- (1) A network of field experiments across European biogeographical regions and pedoclimatic conditions that demonstrate

Table 1 Research projects of the European Crop Diversification Cluster

Project	Full name	Coordinator(s)	Duration
DIVERSify	Designing InnoVative plant teams for Ecosystem Resilience and agricultural sustainability	Alison Karley (UK)	2017–2021
ReMIX	Redesigning European cropping systems based on species MIXtures	Eric Justes and Jean-Noël Aubertot (France)	2017–2021
TRUE	TTransition paths to sUustainable legume-based systems in Europe	Pietro Iannetta (UK)	2017–2021
LegValue	Fostering sustainable legume-based farming systems and agri-feed and food chains in the EU	Frédéric Muel (France)	2017–2021
Diverfarming	Crop diversification and low-input farming across Europe: from practitioners engagement and ecosystems services to increased revenues and chain organization	Raúl Zornoza (Spain)	2017–2022
DiverIMPACTS	Diversification through Rotation, Intercropping, Multiple cropping, Promoted with Actors and value-Chains Toward Sustainability	Antoine Messéan (France)	2017–2022



Fig. 2 Relationships between crop diversification cluster projects.

benefits of crop diversification in terms of productivity, ecosystem services and market opportunities;

(2) A harmonized and consistent set of indicators to assess the sustainability performance of crop diversification at the field, farm, value chain and landscape levels as well as a toolbox to assist agrifood system actors in the selection of appropriate indicators for sustainability assessment;

(3) Services to farmers and agronomists (advice, decision-support and precision agriculture) to help them manage and monitor their transition to more diversified cropping systems;

(4) Learning-for-innovation and multiactor platforms to network case studies and crop diversification experiences across Europe;

(5) Technical and organizational solutions to remove barriers to crop diversification as well as economic approaches and incentives to promote new business models along value chains;

(6) Development of new products or products with enhanced value for the food/feed or industrial sectors (e.g., hemp for insulation boards in the building sector, field peas and other pulses for the food sector, short-chain fresh vegetables and higher protein level for wheat under intercropping).

Also, policy recommendations will be made to foster the

development of crop diversification. In the form of policy briefs, they will focus on the project outcomes within the context of the following policies: the UN Sustainable Development Goals, the reform of the Common Agricultural Policy, the UK Agriculture Act, the EU Farm to Fork strategy and Food security. At the CDC level, special attention is paid to ensure consistency in the policy messages developed by each project and to deliver common messages to the different stakeholders.

Special attention has been paid to scientific communication. The Cluster organized the first European Conference on Crop Diversification in September 2019 in Budapest which gathered more than 200 international delegates^[21]. Several workshops were held and themes such as collaboration among the projects, breeding issues, policy recommendations, and technological and value chain issues were discussed. In addition, the projects held meetings back-to-back with the congress of the European Society of Agronomy in 2018 and 2020. DIVERSify and ReMIX hosted the Intercropping for Sustainability Conference co-organized with agricultural stakeholders in January 2021. The event included scientific sessions, workshops and panel debates to discuss the practical adoption of intercropping, applying research findings, and new and emerging tools and kit. ReMIX and DIVERSify organized the event “Intercropping to boost agroecology in European agriculture” in March 2021 attended by European policymakers and advisors, and the Cluster projects contributed to panel discussions. Additional conferences and webinars will be held in 2021 and 2022 to share the results, boost international collaborations and maintain the momentum

toward the creation of a European network on crop diversification;

(7) International cooperation beyond Europe is also a priority for the Cluster. A symposium entitled “Crop diversification to ensure sustainable food supply for the global population” was organized at the American Association for the Advancement of Science 2020 conference. Exchanges with China are foreseen to help increase the global knowledge on diversification. The Cluster has developed an external website to support communication and dissemination alongside an internal workspace for all working groups to share documents and other information.

7 OUTLOOK ON FUTURE RESEARCH ON CROP DIVERSIFICATION IN EUROPE

The European Commission, through its Green Deal and the Farm to Fork strategies, has set ambitious and coherent goals for more sustainable agriculture^[10]. European policies will need to be adapted to support all actors of crop diversification to reach these ambitious objectives^[22].

In addition to producing new scientific and technical knowledge to speed up the transition toward agrifood systems compatible with these goals, European agricultural research faces a paradigm shift in its organization, approaches and methods: capitalizing on past and existing projects, boosting multiactor and impact-oriented projects and adopting a more holistic approach. In the upcoming calls of Horizon Europe, crop diversification remains a major entry point in several topics of the program “Food, Bioeconomy, Natural resources, Agriculture and Environment”.

The Cluster is working on a legacy plan to pursue its activities on

crop diversification in the future, beyond the lifetime of the individual projects. To this end the CDC intends to set up and maintain a network as well as an online platform to host outputs of CDC projects and support networking on crop diversification:

- (1) Improve visibility of CDC and more broadly crop diversification initiatives in the EU;
- (2) Build on previous experiences rather than start from scratch for upcoming projects/initiatives;
- (3) Share resources (data, experiments, tools and services) related to crop diversification for scientists, policymakers and all stakeholders of the agrifood chain; and
- (4) Create synergies across initiatives over time by hosting upcoming resources.

8 CONCLUSIONS

The six projects of the European Crop Diversification Cluster funded by the EU address knowledge gaps at all levels of the agrifood system that hinder crop diversification development as a way toward an agroecological transition of European agriculture. Propositions of reorganization of the agrifood system and changes to agricultural policies and regulatory systems will be made to enable and boost crop diversification progress. The creation of a European network on crop diversification will ensure the scientific and operational legacy of the Cluster projects.

The large-scale implementation of locally-adapted diversification strategies at the European scale will be a major leap toward the challenges of sustainable food and feed production and environmental preservation, supporting the ambitions laid out in the 2019 European Green Deal.

Acknowledgements

The projects involved in the Cluster have received funding from the EU Horizon 2020 research and innovation program under grant agreement Nos. 728003 (Diverfarming), 727482 (DiverIMPACTS), 727284 (DIVERSify), 727217 (ReMIX), 727672 (LegValue) and 727973 (TRUE), and by the Swiss State Secretariat for Education, Research and Innovation (SERI) under contract number 17.00092.

Compliance with ethics guidelines

Antoine Messéan, Loïc Viguier, Lise Paresys, Jean-Noël Aubertot, Stefano Canali, Pietro Iannetta, Eric Justes, Alison Karley, Beatrix Keillor, Laura Kemper, Frédéric Muel, Barbara Pancino, Didier Stilmant, Christine Watson, Helga Willer, and Raúl Zornoza declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

REFERENCES

- Díaz S, Settele J, Brondízio E, Ngo H T, Guèze M, Agard J, Arneth A, Balvanera P, Brauman K, Butchart S, Chan K, Garibaldi L, Ichii K, Liu J, Subramanian S M, Midgley G, Miloslavich P, Molnár Z, Obura D, Pfaff A, Polasky S, Purvis A, Razaque J, Reyers B, Roy Chowdhury R, Shin Y J, Visseren-Hamakers I, Willis K, Zayas C. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. *IPBES*, 2019
- Campbell B M, Beare D J, Bennett E M, Hall-Spencer J M, Ingram J S I, Jaramillo F, Ortiz R, Ramankutty N, Sayer J A, Shindell D. Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecology and Society*, 2017, **22**(4): art8
- Grunwald S, Thompson J A, Boettinger J L. Digital soil mapping and modeling at continental scales: finding solutions for global issues. *Soil Science Society of America Journal*, 2011, **75**(4): 1201–1213
- Hallmann C A, Sorg M, Jongejans E, Siepel H, Hofland N, Schwan H, Stenmans W, Müller A, Sumser H, Hörrén T, Goulson D, de Kroon H. More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PLoS One*, 2017, **12**(10): e0185809
- Helgason T, Daniell T J, Husband R, Fitter A H, Young J P W. Ploughing up the wood-wide web? *Nature*, 1998, **394**(6692): 431
- Intergovernmental Panel on Climate Change (IPCC). Climate Change 2014: Synthesis Report Summary Chapter for Policymakers. *IPCC*, 2014, 1–32
- Laurance W F, Sayer J, Cassman K G. Agricultural expansion and its impacts on tropical nature. *Trends in Ecology & Evolution*, 2014, **29**(2): 107–116
- Vermeulen S J, Campbell B M, Ingram J S I. Climate Change and Food Systems. *Annual Review of Environment and Resources*, 2012, **37**(1): 195–222
- Frison E A. (IPES-Food). From uniformity to diversity: a paradigm shift from industrial agriculture to diversified agroecological systems. Louvain-la-Neuve (Belgium): *IPES*, 2016
- European Commission. Farm to Fork Strategy, for a fair, healthy and environmentally-friendly food system. *European Commission*, 2020
- Goldringer I, Serpouly-Besson E, Rey F, Costanzo A. Varieties and populations, for on-Farm participatory plant breeding. *Diversifood Innovation Factsheet #2*, 2017. Available at Diversifood website on May 20, 2021
- Renard D, Tilman D. National food production stabilized by crop diversity. *Nature*, 2019, **571**(7764): 257–260
- Beillouin D, Ben-ari T, Makowski D. Evidence map of crop diversification strategies at the global scale. *Environmental Research Letters*, 2019, **14**: 123001
- Duru M, Therond O, Martin G, Martin-Clouaire R, Magne M A, Justes E, Journet E P, Aubertot J N, Savary S, Bergez J E, Sarthou J P. How to implement biodiversity-based agriculture to enhance ecosystem services: a review. *Agronomy for Sustainable Development*, 2015, **35**(4): 1259–1281
- Magrini M B, Anton M, Cholez C, Corre-Hellou G, Duc G, Jeuffroy M H, Meynard J M, Pelzer E, Voisin A S, Walrand S. Why are grain-legumes rarely present in cropping systems despite their environmental and nutritional benefits? Analyzing lock-in in the French agrifood system. *Ecological Economics*, 2016, **126**: 152–162
- Meynard J M, Charrier F, Fares M, Le Bail M, Magrini M B, Charlier A, Messean A. Socio-technical lock-in hinders crop diversification in France. *Agronomy for Sustainable Development*, 2018, **38**(5): 54
- Morel K, Revoyron E, San Cristobal M, Baret P V. Innovating within or outside dominant food systems? Different challenges for contrasting crop diversification strategies in Europe. *PLoS One*, 2020, **15**(3): e0229910
- Preissel S, Reckling M, Schläfke N, Zander P. Magnitude and farm-economic value of grain legume pre-crop benefits in Europe: A review. *Field Crops Research*, 2015, **175**: 64–79
- Martin A E, Collins S J, Crowe S, Girard J, Naujokaitis-Lewis I, Smith A C, Lindsay K, Mitchell S, Fahrig L. Effects of farmland heterogeneity on biodiversity are similar to—or even larger than—the effects of farming practices. *Agriculture, Ecosystems & Environment*, 2020, **288**: 106698
- Palomo-Campesino S, González J A, García-Llorente M. Exploring the connections between agroecological practices and ecosystem services: A systematic literature review. *Sustainability*, 2018, **10**(12): 4339
- Messean A, Drexler D, Heim I, Paresys L, Stilmant D, Willer H. First European Conference on Crop Diversification: Book of Abstracts. Budapest: *INRA and ÖMKI*, 2019
- Guyomard H, Bureau J C, Chatellier V, Detang-Dessendre C, Dupraz P, Jacquet F, Reboud X, Requillart V, Soler L G, Tysebaert M. Research for AGRI Committee—The Green Deal and the CAP: policy implications to adapt farming practices and to preserve the EU's natural resources. Brussels: *European Parliament, Policy Department for Structural and Cohesion Policies*, 2020