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## Availability and integration of agro-environmental data: the French case

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### Abstract

*This chapter addresses collection and integration of large amounts of data from a variety of sources when developing agronomic approaches at the landscape and territory levels. Data commonly used in agro-environmental studies are climate, soils, land cover and land use (including cropping practices). They are used as inputs for indicator- or model-based assessment methods. Additional information is now required for agroecological studies, such as spatial distribution of weeds, pests and diseases; biodiversity; or landscape features. Gathering and using this scattered and heterogeneous information for integrated studies at watershed, regional or national levels still requires further methodological efforts. Remote sensing is a source of data that continuously progresses in spatial and temporal resolution, and accessibility. Such integrative approaches are illustrated for a case study in France. The next challenges and opportunities for data collection, integration and governance are discussed, with a focus on mainland France.*

**Keywords:** climatic data, soil data, land cover, cropping practices, remote sensing, maps, databases

**Introduction:** *what kind of agro-environmental data for which end-uses?*

In agronomy, studies are increasingly performed at watershed, regional and national levels, generally supported by integrated assessment and modeling (Jakeman and Letcher, 2003) and combining input data on the physical and biological environment, land cover, cropping practices and socio-economics (Ewert *et al.*, 2009; Ewert *et al.*, 2011; Justes *et al.*, 2012; Boiffin *et al.*, 2014). These studies refer to emerging fields

of agronomy such as (i) landscape and territorial agronomy (Benoit *et al.*, 2012), which focuses on relationships among farming practices, natural resources (e.g. soil, water, biodiversity) and landscape patterns, and (ii) global agronomy (Makowski *et al.*, 2014), which operates at larger spatial scales. Analyzing interactions between agriculture and the environment or assessing performances of crop-production systems at supra-farm levels now requires collecting data on the spatial distribution of land-cover types and characteristics of farming systems (Janssens *et al.*, 2009). Previously, these agro-environmental data had to be collected and organized in databases to make them easily and freely reusable for a wide range of applications and stakeholders. In most cases, however, the literature mentioned a lack of accessible and reliable data on physical (e.g. available soil water content) and technical characteristics (e.g. farm practices) as a main obstacle to rapid development of these new fields. One methodological challenge is to improve the description and location of cropping systems at the regional level (Leenhardt *et al.*, 2010). According to Sebillotte (1974), cropping systems are defined at field and farm levels by several decisions made by a farmer: (i) the choice of land cover (nature of crops and grasslands), (ii) their spatial (crop planning at field or islet levels) and temporal arrangements (crop sequences) and (iii) the land-use management for crop production and other services. A second challenge lies in describing relationships between cropping systems and natural resources, such as water resources or landscape biodiversity. Doing so requires data on characteristics and the location of these natural resources but also on spatio-temporal interactions between cropping systems and these resources. Data needed to characterize cropping systems in agronomic or environmental studies at supra-field levels usually concern climate, soils, land cover and cropping practices but increasingly landscape features and biodiversity; these data serve as inputs for indicator- or model-based assessment methods (e.g. Bockstaller *et al.*, 2008; Constantin *et al.*, 2015a; Tibi and Therond, 2018). Most common data come from meteorological stations that cover France, soil prospection and mapping, and periodic surveys at the farm level for farming practices. Besides historical and recent climatic records, climatic projections based on Intergovernmental Panel on Climate Change (IPCC) scenarios are increasingly used to assess impacts of climate change on agriculture and potential adaptation options (Brisson and Levrault, 2010). In addition, remote sensing (satellite imagery) can deliver more easily land-cover and crop-management information about large areas with a good spatial resolution (ca. 1-10 m) and temporal frequency (ca. 10-15 days). Collecting and using this scattered and heterogeneous information effectively for integrated assessment approaches at the territory level still requires methodological efforts. In this chapter, we describe the agro-environmental data currently available to agronomists in France for such territorial surveys and integrated studies, with a focus on the crop-production sector. A case study illustrates the practical use and integration of these data. Finally, we discuss the practical and methodological problems that integrating these data into coherent chains of models poses for producing relevant information in agro-environmental studies.

## **A. Data description**

Tables 1 to 6 in the Appendix present a brief overview of the data detailed in Section A: data collection networks, methods used to collect data, spatial and temporal scales, data accessibility for research and data providers.

Two important components of the socio-ecological system were omitted from this review: livestock production and socio-economics (markets, prices). These data are usually produced at the farm level. Economic and agricultural data of the Farm Accountancy Data Network (RICA) can be used, for instance, to produce indicators of environmental impacts of agricultural systems (Samson *et al.*, 2012).

### **1. Environmental data**

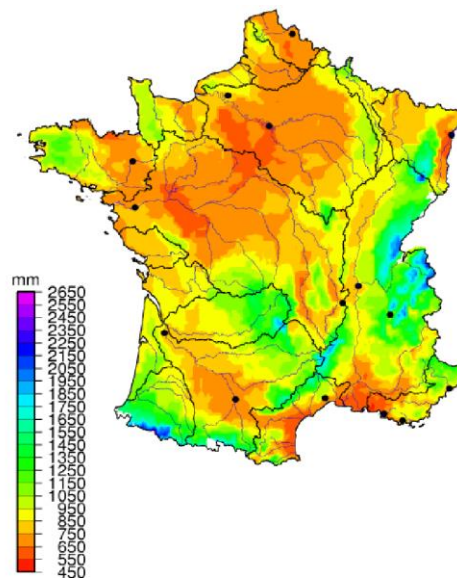
#### *1.1. Climatic data*

The main variables recorded at local weather stations (at a height of 2 m) are temperature (minimum and maximum), relative humidity (minimum and maximum), precipitation (amount and intensity), wind (speed and direction) and global solar radiation. Additional variables may include photosynthetically active radiation, wetness duration, the actinothermic index and soil temperature at different depths. Variables such as potential evapotranspiration using Penman or Penman-Monteith equations (Penman, 1956; Monteith, 1965) can be calculated from measured variables. Data are usually recorded hourly and then aggregated into daily values.

Météo-France<sup>1</sup> is the main provider of climatic data in France. It manages a network (Radome) of more than 600 automatic weather stations throughout France. Other private and public organizations supplement this network, including INRAE, which manages a national agroclimatic network<sup>2</sup> of 55 weather stations to collect data close to long-term experiments and phenotyping platforms. Historical records are also available over long time series through web applications (“Publithèque<sup>3</sup>” and “Climatik<sup>4</sup>” from Météo-France and INRAE, respectively).

According to the spatio-temporal scales of the studies, Météo-France provides either raw data or processed products, such as:

- 10-day, monthly or annual data summaries at multiple spatial scales
- past climatic series after statistical correction and homogenization as a baseline reference when exploring climate change
- an 8-km-resolution daily atmospheric reanalysis for mainland France (SAFRAN), composed of 8602 cells (8 km × 8 km) available from September 1958 to the present (Vidal *et al.*, 2010) (Figure 1)



**Figure 1.** Annual amount of precipitation (mm) using daily atmospheric reanalysis for mainland France (1961-1990); SAFRAN 8 km × 8 km cells (source: Météo-France)

When studying agroecosystems at watershed or territory levels, methods of spatio-temporal “data rebuilding” may be necessary. For instance, agrometeorologists from INRAE have helped (i) reconstitute altitudinal gradients of temperature in hilly or mountains areas (Huard, 2011); (ii) apply statistical methods of regionalization to climate projection data (Déqué, 2007); (iii) project climatic data (mainly precipitation) at a finer scale to characterize relationships between climatic variables and physical properties of the

<sup>1</sup> <http://www.meteofrance.fr/>

<sup>2</sup> <http://w3.avignon.inra.fr/carto/>

<sup>3</sup> <http://publithèque.meteo.fr/okapi/accueil/okapiWebPubli/index.jsp>

<sup>4</sup> [https://intranet.inra.fr/climatik\\_v2](https://intranet.inra.fr/climatik_v2)

environment that influence the landscape and (iv) reconstitute finely climatic data for impact models that require such downscaling.

For climate change studies, the DRIAS<sup>5</sup> portal provides climatic projections on the SAFRAN grid obtained after running three regional climatic models (ensemble approach using CNRM2014, IPSL2014 and CORDEX) and for the greenhouse-gas-emission scenarios of the IPCC (i.e. SRES, RCP). Most of these data are free-of-charge for research uses, and some of them are not restricted to users in France.

Climatic data are used intensively to explore climate change (e.g. Brisson and Levrault, 2010) or in agrometeorological studies (e.g. phenological survey, drought survey, crop suitability). Agro- and eco-climatic indicators are calculated from historical records or for future scenarios when evaluating the vulnerability of crops and cropping systems to climatic variation and long-term change (Caubel *et al.*, 2015).

### 1.2. Soil data

In the late 1990s, a national study (Bornand, 1997) identified weaknesses of French soil inventory and monitoring programs. Given the growing concern for preservation of national soil resources, the French ministries for Agriculture and Environment, the French environment and energy management agency (ADEME) and INRA decided to join forces to build a French soil information system to provide national soil data that met the needs of policy makers and researchers. The GIS Sol<sup>6</sup> (French Soil Scientific Interest Group) was launched in 2001.

Since then, soil data have been collected at the national level according to complementary inventory and monitoring strategies that rely on both using legacy data and acquiring new data. Data collection is coordinated by the INRAE InfoSol Unit in Orléans through networks of ca. 30 regional institutions with skills in soil science and ca. 20 laboratories that analyze soil.

A harmonized multi-scale soil inventory program provides soil maps associated with spatial databases. Currently, a 1:1 000 000 geographical database<sup>7</sup> is available for all of mainland France (Figure 2), while a 1:250 000 scale, which covers 94% of mainland France, should be finished by 2023 (Laroche *et al.*, 2014). Soil maps and databases are also available at larger scales that range from 1:100 000 to 1:10 000 (Richer de Forges *et al.*, 2014), with the latter developed more often for areas that represent larger zones with a specific issue (e.g. drainage). Besides the 1:1 000 000 database, which is the French contribution to the European Union (EU) Geographical Soil Database (2004), these databases are developed according to national specifications, including the French national soil data standard DoneSol (Grolleau *et al.*, 2004). Once validated, databases are available on request to INRAE or regional data providers. Gradually, they will be available through web platforms called Websol<sup>8</sup> (Vinatier *et al.*, 2013), developed by a group of data providers in the framework of the Mixed Technological Network (RMT) "Soils and Territories"<sup>9</sup> which promotes the use of soil data for decision making.

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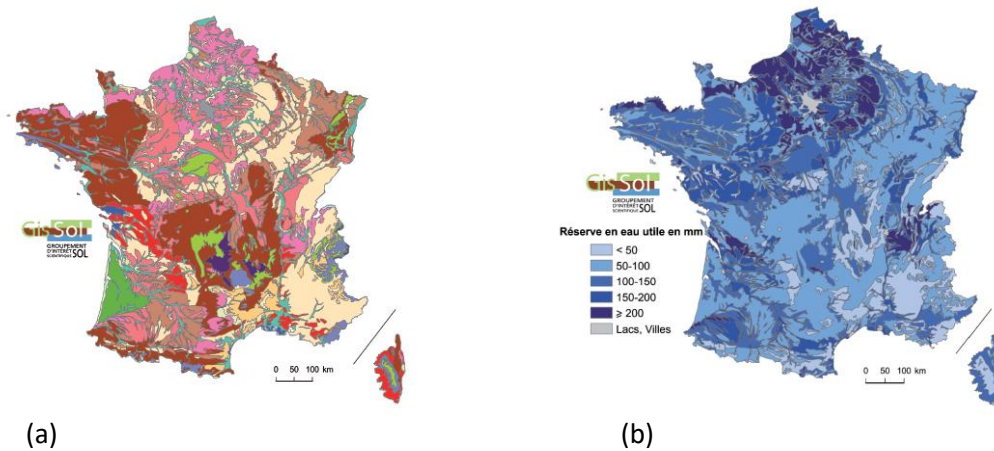
<sup>5</sup> <http://www.drias-climat.fr/>

<sup>6</sup> The French Soil Scientific Interest Group includes the Ministry of Ecology and Solidarity Transition; Ministry of Agriculture and Food, French Environment and Energy Management Agency; French National Research Institute for Agriculture, Food and Environment; French National Research Institute for Development and National Institute of Geographic and Forest Information.

<sup>7</sup> <https://doi.org/10.15454/BPN57S>

<sup>8</sup> <http://infosol.websol.fr>

<sup>9</sup> <http://www.sols-et-territoires.org>



**Figure 2.** Two maps from the GIS Sol (1:1 000 000 scale): (a) dominant soil types (14 classes) and (b) available soil water content (mm). Source: <https://www.gissol.fr>

In addition, monitoring programs provide two types of information about dynamics of soil parameters. First, a soil test database, which is computerized and standardized, collects results of analyses performed for farmers by soil analysis laboratories. This program currently stores more than 20 million analytical results going back to the 1990s and covers all of mainland France. For confidentiality reasons, individual results are not accessible. Statistical results at several levels of spatial aggregation are accessible to the public *via* an interactive map on a web server<sup>10</sup> and *via* download from the INRAE data portal<sup>11</sup> (Saby *et al.*, 2014). Temporal data can be compared visually in 5-year periods. Statistical data from a specific program to collect heavy metal analyses (BDETM) (Duigou *et al.*, 2011) is also available for download from the INRAE data portal<sup>12</sup>. These programs provide spatial and temporal views of the distribution and dynamics of many parameters in agricultural topsoil layers in France. The data are contained in a national database that is integrated within the national soil information system. The quality of all data, particularly their consistency, is checked. Second, a national soil-monitoring network was established in 2001 (Arrouays *et al.*, 2003). It is based on a grid of 16 km × 16 km cells, with 2200 sites expected to be sampled every 15 years. At each site, composite samples are taken from topsoil (0-30 cm) and subsurface (30-50 cm) layers. Samples are analyzed several times to measure agronomic parameters, contaminants, and physical and biological properties. Agricultural practices are also monitored at the sites. The first sampling campaign was performed in 2009 and contributed greatly to the first detailed assessment of the state of soils in France (Antoni *et al.*, 2011). The second campaign began in 2016, will end in 2027 and will soon enable changes in parameters to be detected. Once their consistency has been checked, the data will be available on request from INRAE, except for the exact location sampling sites, according to national rules on personal data. Data are also increasingly available through web services<sup>13</sup> and on the INRAE data portal<sup>8</sup>.

Samples from inventory and monitoring programs are archived in a National Soil Archive managed by INRAE. It enables (i) detection of potential analytical changes and comparison of analytical results between sampling campaigns, (ii) *a posteriori* analysis according to emerging issues or new analytical methods and (iii) development of innovative approaches for mapping new soil parameters at the national level.

<sup>10</sup> <https://webapps.gissol.fr/geosol/>

<sup>11</sup> <https://data.inra.fr/dataverse/gissol/>

<sup>12</sup> <https://doi.org/10.15454/4GNNOS>

<sup>13</sup> <http://www.gissol.fr>

Data collected according to these approaches are contained in the integrated national soil information system. Its components enable one not only to store collected data, but also to check data quality, process data from multiple sources in a consistent manner, store processed data and scripts, and provide digital products such as web services or dynamic mapping of soil properties. Each step from storage to digital products is traced, and updates to collected data also update the digital products.

Data are widely used to understand and map spatial distributions of soil properties, such as contents of phosphorus (e.g. Delmas *et al.*, 2015), trace elements (e.g. Saby *et al.*, 2011), organic contaminants (e.g. Villaneau *et al.*, 2011) or carbon (e.g. Martin *et al.*, 2011a), as well as microbial communities (e.g. Dequiedt *et al.*, 2011). They also enable detection of changes in soil properties such as carbon content (e.g. Orton *et al.*, 2012) or agronomic parameters such as phosphorus content (e.g. Lemerrier *et al.*, 2008).

On areas of bare soil, remote sensing can help greatly to estimate permanent properties of soils. For instance, reflectance data can be used to map topsoil organic carbon content (Vaudour *et al.*, 2013) or clay content (Shabou *et al.*, 2015). These methods are not yet operational, but they are promising. Digital soil mapping approaches were recently developed to produce, according to GlobalSoilMap specifications (Mulder *et al.*, 2016, Roman Dobarco *et al.*, 2019), national maps of soil properties and their associated uncertainties, which have high potential as input data for modeling. Data from the national soil information system have already been used in a variety of crop and soil models, such as STICS (e.g. Durandeu *et al.*, 2010), CENTURY and RothC (e.g. Martin *et al.*, 2011b).

### 1.3. Biodiversity data

According to the Convention on Biological Diversity from the United Nations (1992), biodiversity is “the variability among living organisms from all sources including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems”. We focus here on networks that collected data on a single component of biodiversity or on indicators of biodiversity that are of key interest for agriculture.

From an historical perspective, observation of biodiversity in agricultural areas focused initially on plant pathogens, animal pests and weeds because of their potential to damage crops. The main motivation was to help design strategies to control these pests, or at least to warn farmers about potential biotic threats. With the recent advent of agroecology and the growing awareness of detrimental impacts of intensive agriculture on biodiversity, data collection was expanded to include non-pest organisms in a definition of general biodiversity (pest and non-pest species). Consequently, we present data-collection networks for pests (plant pathogens, animal pests, and weeds) and general biodiversity on agricultural land separately.

#### 1.3.1. Data on plant pathogens, animal pests and weeds

In the late 19<sup>th</sup> century, pests such as the Colorado beetle (*Leptinotarsa decemlineata*), late blight (*Phytophthora infestans*) on potatoes (*Solanum tuberosum*) and phylloxera (*Daktulosphaira vitifoliae*) on grapevines (*Vitis vinifera* L.) exerted such levels of biotic stress that monitoring pest species and creating a warning system about them became essential to farming. To this end, the French government created the “Phytopathological Service<sup>14</sup>” in 1911, which became the Plant Protection Service<sup>15</sup> in 1941. This service produced agricultural pest warnings<sup>16</sup> for several crops as early as 1943 (Agerberg *et al.*, 2011). These warnings were broadcast on a regular basis at departmental or regional levels, with a frequency that depended on the season. In 2010, the French Ministry of Agriculture organized a Territory Biological Monitoring<sup>17</sup> system within the national ECOPHYTO program for pesticide reduction, which serves as a basis for developing warning bulletins on plant health (“Bulletins de Santé du Végétal” or BSV).

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<sup>14</sup> Service phytopathologique

<sup>15</sup> Service de la Protection des Végétaux

<sup>16</sup> “Avertissements Agricoles” until 2009, then re-named “Bulletins de Santé du Végétal”

<sup>17</sup> Surveillance Biologique du Territoire

The “Flora Biovigilance Network”<sup>18</sup> was established by the French Ministry of Agriculture in 2002. Its main objective is to monitor potential unintended effects of innovative cropping practices (including genetically modified crops) on flora and fauna in agroecosystems (Délos *et al.*, 2006; Fried *et al.*, 2007). In its early years, ca. 1000 crop fields throughout France were monitored annually. In each field, vegetation was monitored comprehensively, along with cropping practices, key soil properties (pH and texture) and the field environment. Fried (2007) and Borgy (2011) used the underlying database to analyze drivers of weed community patterns.

In the ECOPHYTO program, epidemiological surveillance networks were created to share basic observations at the field level in the national database Epiphyt. Data on epidemics and infestations are collected in agricultural and non-agricultural areas for a wide range of crops using harmonized protocols. The Vigiculture network, launched by the main French extension institutes (Arvalis-Institut du Végétal, Terres Inovia), contributes greatly to development of the Epiphyt database.

As mentioned, no data on pests seem to have been collected at the landscape level itself. However, data on pests are also available in archives of extension institutes and Chambers of Agriculture (Agerberg *et al.*, 2011). These data are scattered and difficult to identify but may contain specific data on a given pest collected at the landscape level, such as from systematic monitoring of phoma stem canker (*Leptosphaeria maculans* and *L.biglobosa*) in oilseed rape (OSR) fields in a 4.5 km × 4.5 km square in the Centre region by Terres Inovia (Boillot *et al.*, 2008), a regional agronomic survey of phoma black stem (*Phoma macdonaldii*) on sunflower in 34 commercial fields over 5 years in the Lauragais region (Bordat *et al.*, 2011) and annual surveys of sunflower diseases by Terres Inovia (2016). Other potential sources of information include archives of Regional Federations for Defense against Pests<sup>19</sup> and Departmental Federations of Defense Groups against Pests<sup>20</sup>, but it is unlikely that their data were collected at the landscape level.

### 1.3.2. Data on general biodiversity (pest and non-pest species)

The Territory Biological Monitoring system has two axes: (i) an epidemio-surveillance<sup>21</sup> program for plants, for which warning bulletins on plant health are only the “tip of the iceberg” (e.g. forest health; regulated and emerging organisms, with an active monitoring network and passive monitoring *via* unsupervised reports), and (ii) monitoring of unintentional effects<sup>22</sup> (e.g. pesticide resistance, potential impacts of pesticides on non-target organisms). For the latter axis, several partners (i.e. Chambers of Agriculture, Regional Federations for Defense against Pests, private companies and INRAE) collect data from multiple field networks on earthworms in fields and birds, flora and coleopterans in field margins. These data are not collected at the landscape level, but can be considered to represent regional landscapes if the associated fields are georeferenced.

The French Ministry of Ecology published a summary document with the data available on biodiversity (Pappalardo *et al.*, 2010). Although it focuses on natural areas, it contains large amounts of information about networks that monitor biodiversity. Among them, the Soil Quality Measurement Network (RMQS)<sup>23</sup>, through its BIODIV component, monitors biological components of agricultural soils in temperate zones and their activity. It evaluates parameters that define structural and functional biodiversity, and analyzes potential relationships among parameters used to describe soil quality and biological components. It considers a wide range of organisms, such as microorganisms, nematodes, micro-arthropods, earthworms and total macrofauna (Figure 3).

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<sup>18</sup> Réseau Biovigilance Flore

<sup>19</sup> FREDON: Fédérations Régionales de Défense contre les Organismes Nuisibles

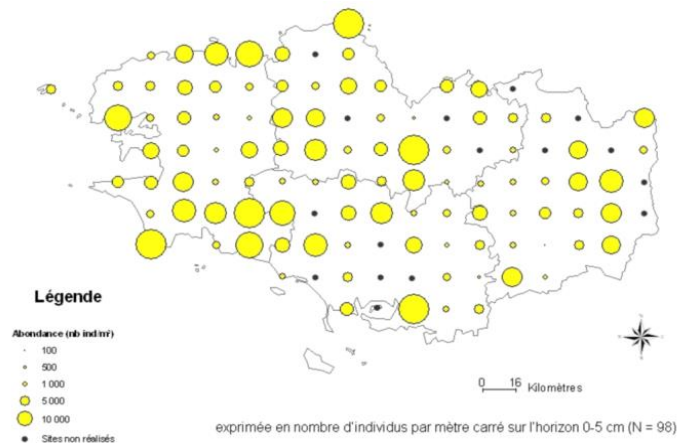
<sup>20</sup> FDGDON: Fédérations Départementales des Groupements de Défense contre les Organismes Nuisibles

<sup>21</sup> Epidémiosurveillance végétale

<sup>22</sup> Suivi des Effets Non Intentionnels (ENI)

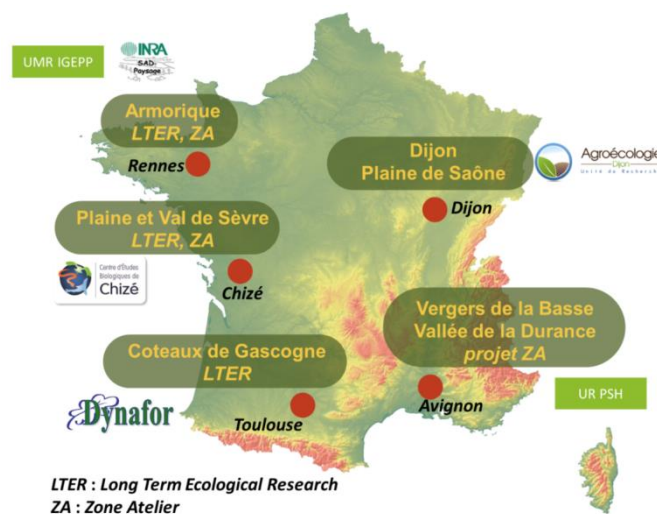
<sup>23</sup> Réseau de Mesure de la Qualité des Sols (RMQS)





**Figure 3.** Example of data available in the BIODIV network of the Soil Quality Measurement Network: abundance of springtails (*Collembola*) in Brittany (France), expressed as number of individuals per m<sup>2</sup> on 0-5 cm soil layer.

A network to monitor ecosystem services provided by biodiversity in agricultural landscapes (SEBIOPAG)<sup>24</sup> was launched in 2013. It relies on five sites (workshop zones and/or long-term ecological research sites, Figure 4). It is a research instrument of Ecoscope, the flagship program of the French Foundation for Research on Biodiversity<sup>25</sup>. Besides monitoring ecosystem services, SEBIOPAG also monitors their drivers (e.g. landscape structure, cropping practices) and the dynamics of both as a function of global changes (e.g. in land use, climate, the economic context or regulations). The ecosystem services studied are pest regulation by beneficial organisms and pollination, with a special focus on the influence of weeds on pollination and predation.



**Figure 4.** The five French sites of the SEBIOPAG network.

Several partners of the Mixed Technological Network (RMT) on “Biodiversity and Agriculture”<sup>26</sup> launched initiatives to characterize biodiversity in agroecosystems. The “Biodiversity” network of the national agricultural education program<sup>27</sup> contributes to three specific networks: Apiformes, Agrifaune and Messicoles (albeit with no data collected at the landscape level). The Apiformes network monitors wild

<sup>24</sup> Réseau pour l'étude des Services Ecosystémiques assurés par la Biodiversité dans les Paysages Agricoles (<http://sebiopag.inrae.fr>)

<sup>25</sup> Fondation pour la Recherche sur la Biodiversité (FRB)

<sup>26</sup> <http://www.rmt-biodiversite-agriculture.fr/>

<sup>27</sup> Réseau thématique “Biodiversité” de l'enseignement agricole (<http://www.reseau-biodiversite.educagri.fr/>)

and domesticated bees and trains students in agricultural secondary schools about them. It observes several sites repeatedly according to harmonized protocols. The Agrifaune network<sup>28</sup>, created in 2006, launched a program in 2008 to monitor agricultural, environmental, economic and faunal performances at the farm level.

Since 2009, the Ministry of Agriculture has coordinated the Agricultural Observatory of Biodiversity<sup>29</sup>, which aims to (i) develop a database on associated biodiversity and (ii) heighten awareness of this biodiversity and provide methodological support to farmers for observing it. This observatory relies on scientific participatory approaches performed by the National Museum of Natural History and is a part of the Vigie-Nature program, for which a network of volunteers monitors common species of flora and fauna throughout France. Currently, it provides four protocols to farmers who volunteer to collect data on bees, butterflies, earthworms and terrestrial invertebrates. Explanatory variables are also collected, such as observation dates, weather variables, cropping practices and landscape characteristics.

In addition to national initiatives, Regional Biodiversity Observatories<sup>30</sup> were launched in 2011 in association with the National Biodiversity Observatory<sup>31</sup>. Their main objectives are to (i) analyze and share information about regional biodiversity, (ii) summarize available information, (iii) monitor biodiversity, (iv) assess the stresses exerted by and impacts of corrective measures, (v) improve knowledge about biodiversity, (vi) communicate, (vi) provide support to local authorities and (vii) bring together local stakeholders.

The ARBRE<sup>32</sup> network was established in 2010 by volunteer farmers to integrate biodiversity more into their production systems to address agricultural challenges such as preserving beneficial organisms, decreasing erosion, preserving pollination and facing territorial challenges (e.g. water quality, landscape organization). It was funded by the Maine et Loire General Council, the EU and the Fondation de France. It aims to (i) integrate non-pest biodiversity into production systems and use ecosystem services they provide to decrease inputs (e.g. use beneficial organisms to limit pest populations, i.e. biological control by conservation); (ii) rediscover flora and fauna on farms and prepare for future changes in the EU Common Agricultural Policy (CAP); (iii) share observations, experiences and thoughts among farmers and with specialists; (iv) develop local references on impacts of innovative cropping practices; (v) share and adapt results of current research projects; (vi) help limit the loss of biodiversity and (vii) install landscape infrastructure favorable to wild species and domestic heritage species.

The French Breeding Bird Survey is a monitoring program (established in 2001) in which skilled ornithologists volunteer to count birds according to a standard protocol in the same field each year (Jiguet *et al.*, 2012). It was used notably to analyze whether effects of crops on skylarks (*Alauda arvensis*) differ between the field and landscape levels (Sausse *et al.*, 2015).

The Center for Research through Banding Bird Populations<sup>33</sup> coordinates banding activities of the National Museum of Natural History as well as the Temporal Monitoring of Common Birds<sup>34</sup> program, which is composed of two complementary activities: (i) monitoring spatio-temporal dynamics of common nesting bird populations using a network of listening stations and (ii) monitoring the two main demographic parameters of bird populations (adult survival and reproductive success) by live capture. Similarly, the SPIOLL<sup>35</sup> network quantifies pollinating insects at the national level. It is a participatory scientific project that monitors changes in their diversity over time, along with the structure of pollinating networks. Participants upload pictures that they have taken of pollinating insects into an online database that can be used to perform spatial analyses once the species have been identified.

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<sup>28</sup> <http://www.oncfs.gouv.fr/Amenager-et-developper-les-territoires-ru150/Le-reseau-Agrifaune-ar264>

<sup>29</sup> Observatoire Agricole de la Biodiversité (<http://observatoire-agricole-biodiversite.fr/>)

<sup>30</sup> Observatoires Régionaux de la Biodiversité (ORB)

<sup>31</sup> Observatoire National de la Biodiversité (ONB)

<sup>32</sup> ARBRE: *Agriculteurs Respectueux de la Biodiversité et de la Richesse de l'Environnement* ("Farmers Respectful of Biodiversity and Environmental Wealth")

<sup>33</sup> Centre de Recherches par le Bagueage des Populations d'Oiseaux (CRBPO)

<sup>34</sup> Suivi Temporel des Oiseaux Communs (STOC)

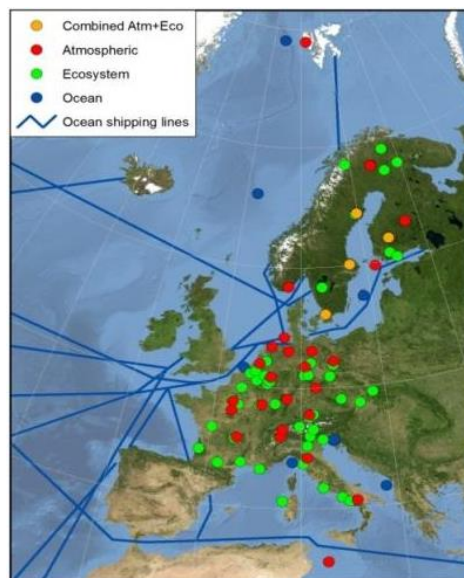
<sup>35</sup> Suivi Photographique des Insectes POLLinisateurs

#### 1.4. Monitoring the status of vegetation, air and soil

This section briefly reviews the observation networks that help monitor gaseous emissions from agricultural land, soil water content and vegetation growth and senescence. These data can be used directly to monitor and assess impacts of agroecosystems on the environment.

##### 1.4.1. ICOS network for flux data

In France, flux data are monitored in 14 ICOS (Integrated Carbon Observation System) sites equipped with flux towers that cover different ecosystems: forests, croplands and grasslands. The national networks are the backbone of the ICOS research infrastructure (> 40 sites in western and northern Europe, Figure 5)<sup>36</sup>. Fluxes of CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, H<sub>2</sub>O and heat are measured by eddy covariance along with ecosystem variables (at vegetation and soil levels) to understand processes behind the exchange of energy and greenhouse gases between the ecosystems and the atmosphere. Data are freely available for research through the FluxNet network (<http://fluxnet.ornl.gov/obtain-data>).



**Figure 5.** Current ICOS stations for atmospheric, ecosystem and ocean measurements.

##### 1.4.2. Remote sensing for monitoring vegetation and soil status

Reflectance data measured in the visible (0.38-0.75  $\mu\text{m}$ ), near-infrared (0.75-1.4  $\mu\text{m}$ ) and short-wavelength infrared (1.4-3.0  $\mu\text{m}$ ) domains are a unique source of information to monitor key variables and properties of soil and vegetation, such as leaf area index, fraction of vegetation cover and canopy structure. Combining reflectance data from different wavelength domains allows vegetation indices (e.g. normalized difference vegetation index) to be calculated, which are effective for monitoring seasonal vegetation dynamics.

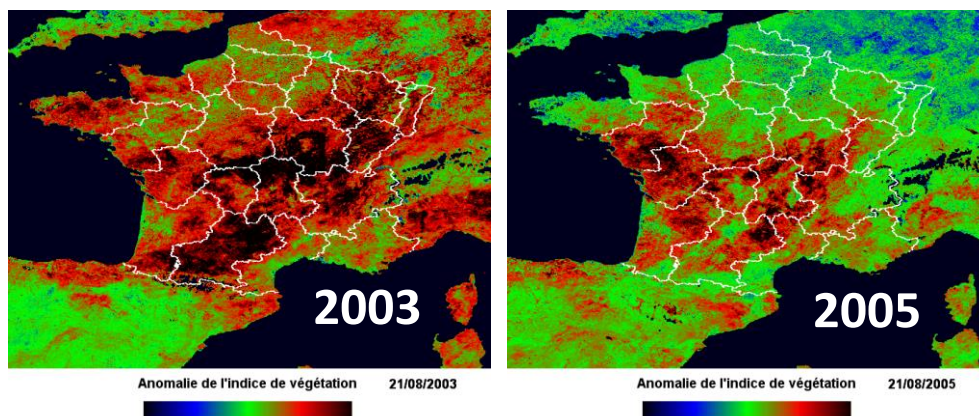
Many remote-sensing products are now produced operationally and becoming increasingly reliable. To obtain these products, it is necessary to correct for atmospheric effects and to detect clouds (Hagolle *et al.*, 2015). Observations at high spatial resolutions (ca. 10-30 m) from Sentinel-2 (since 2015), SPOT (since 1986) and Landsat (since 1972, temporal resolution = 16 days), the main sources of high-resolution data, can be used. Observations at medium spatial resolutions from MODIS (250-1000 m, since 2002), SPOT-VEGETATION (1000 m, 1998-2014) (Figure 6), PROBA-V (since 2013) and Sentinel-3 (300 m, since 2016) can also be used, with the advantage of daily revisits.

<sup>36</sup> <https://www.icos-cp.eu/observations>

Due to cloud cover, synthetic products at a lower temporal resolution of ca. 15 days are produced operationally from these daily observations. These data are generally free and can be downloaded from public web sites of THEIA<sup>37</sup>, Copernicus, ESA or NASA. THEIA provides Sentinel-2 and Landsat data (<http://www.cesbio.ups-tlse.fr/multitemp/>), as well as SPOT archive data through the SPOT World Heritage program. Long-term archives of Landsat data are available from the US Geological Survey (<http://landsat.usgs.gov/>).

Many operational products have been developed to monitor vegetation, including biophysical variables and phenological or water-stress indices. For instance, global time series of many operational products are available, mostly from medium-resolution satellites (ca. 500-1000 m), and provide unique information about biophysical variables of vegetation, such as fraction of green vegetation cover, leaf area index, and fraction of absorbed photosynthetically active radiation (<http://land.copernicus.eu/global/products/>; Baret *et al.*, 2013).

These operational products can be used for many applications, such as monitoring changes in agricultural and forest practices, monitoring vegetation phenology (e.g. leaf unfolding, flowering and senescence dates) (Guyon *et al.*, 2011), evaluating impacts on vegetation structure (e.g. defoliation) due to weather anomalies (i.e. severe droughts) or to insect damage (Samalens *et al.*, 2012; Bories *et al.*, 2012), monitoring long-term trends due to climate change (Nemani *et al.*, 2003) and calculating indices of vegetation water status to estimate crop yields or forest fire risks. Operational methods to calculate more elaborate products such as root-zone soil moisture or soil water-holding capacity, which require combining remote-sensing data and soil-vegetation-atmosphere models, are not yet available.



**Figure 6.** Observations of vegetation anomalies from the SPOT-Vegetation satellite on 21 August in (a) 2003 and (b) 2005. Source: French National Centre for Space Studies (CNES).

Observations made in the thermal infrared domain (e.g. from MODIS or MSG-2) at medium spatial resolution provide daily and global estimates of surface temperature and can be used to monitor vegetation water status and irrigation practices. However, few operational products are available to date for agriculture or forestry (mainly for monitoring fire risk).

Observations made in the microwave domain (from active (radar) or passive systems) use low-frequency radiation (1-100 GHz). They have low or very low sensitivity to atmospheric and solar illumination effects and can sense through vegetation, especially at the lowest frequencies (1-10 GHz); the lower the frequency, the greater the ability to penetrate the atmosphere, clouds and vegetation. These observations thus have the great advantage of allowing vegetation and soil to be monitored under cloud cover. They may have multi-configuration capabilities (i.e. view angle, polarization and frequency) that allow several land-surface parameters to be obtained simultaneously (Wagner *et al.*, 2007). Radar sensors based on the Synthetic Aperture Radar (SAR) technique can have high or very high spatial resolutions (e.g. ca. 10 m for Sentinel-1) (Torres *et al.*, 2012).

<sup>37</sup> THEIA (Pôle Thématique Surfaces Continentales) ([www.theia-land.fr](http://www.theia-land.fr))

Microwave observations are sensitive to vegetation (e.g. biomass, water content, canopy structure) and soil (e.g. soil moisture, roughness, texture) characteristics. Over short vegetation or bare soil, radar can be combined with optical data to monitor vegetation characteristics (e.g. canopy type, biomass, crop height) or soil conditions (e.g. soil moisture, change in roughness due to agricultural practices) (Fieuzal *et al.*, 2011, 2013). Over forests, observations are sensitive mainly to vegetation characteristics and are combined with space-borne Lidar and optical data to map forest dynamics and estimate biomass; these products are now available at a relatively coarse resolution (Asner *et al.*, 2012, Saatchi *et al.*, 2011). The ESA's future Earth Explorer Biomass mission (launch scheduled for 2021) will use very low frequency (P-band) radar to monitor the global carbon cycle in forests. The microwave domain has high potential (especially the recent Sentinel-1 SAR sensors), but methods that use it are not yet operational. For instance, distinguishing soil and vegetation effects may be complex. In addition, speckle (granular noise) effects degrade the quality of images obtained from coherent imaging systems such as SAR. Conversely, operational soil moisture products at coarse resolution (ca. 25 km) have been available since 1980 by combining active (ERS-1 & -2 since 1991, ASCAT) and passive (AMSR-E since 2003, SMOS since 2010) sensors through the ESA/CCI initiative; they allow analysis of the global water cycle, with applications in meteorology and drought monitoring (Al-Yaari *et al.*, 2014). Long-term time series of a vegetation index (vegetation optical depth) also can be produced from passive microwave observations, and it is used increasingly to monitor seasonal changes in the leafy and woody components of vegetation cover.

## **2. Agricultural practices**

### *2.1. Land use and land cover*

In a common sense, land-cover data document how much of an area is covered by forests, grasslands, crops, water and other land-cover types. Land-use data show how people use the landscape, whether for production, conservation or mixed uses. Types of land cover can be managed or used quite differently. Land cover can be determined by analyzing satellite and aerial imagery. The resulting maps provide information to help managers understand the current landscape better and observe changes over time. With this information, managers can evaluate past decisions and gain insight into potential effects of their decisions before they are implemented. However, land-use management cannot be determined directly from satellite imagery; this information comes instead from surveys at field and farm levels.

#### *2.1.1. The French Land Parcel Identification System*

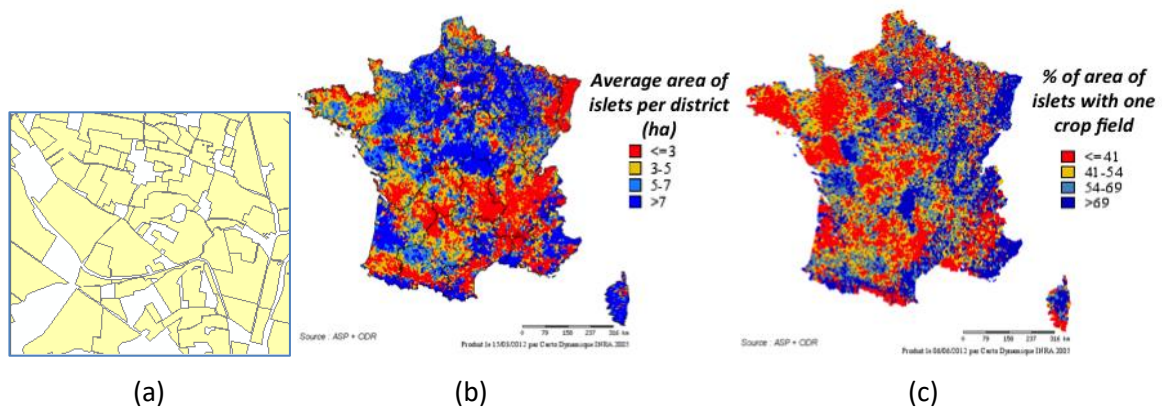
In the EU, each Member State must perform detailed administration and monitoring of annual Common Agricultural Policy (CAP) subsidies allocated to farmers through the development of a geographic information system called "Land Parcel Identification System" (LPIS). Although regulatory requirements were uniform, the Member States chose different technological solutions for their LPIS (Inan *et al.*, 2010; Sagris *et al.*, 2013). Since 2006, the French LPIS, called "Registre Parcellaire Graphique" (RPG), has been created annually by farmers when they apply online for CAP subsidies.

On a 1:5000 orthorectified aerial photograph, farmers must draw or digitize the boundaries of their physical blocks of fields (hereafter, "islets") and provide information about the areas of the crops grown within each one (Figure 7a). The RPG database provides these geographic and attribute data annually for ca. 6 million islets in France (covering 27 million ha). It completely covers the agricultural land with crops and grasslands. It is much less comprehensive for agricultural land not eligible for CAP subsidies, such as vineyards and orchards (Cantelaube *et al.*, 2013). In the database, each islet is tagged to one of ca. 400 000 farms by an identifier. Farmers who contract for agri-environmental measures (funded by the second pillar of the CAP) must also digitize the boundaries of the areas concerned within the RPG islets (e.g. conversion to organic farming, extensive grassland management, decrease in pesticide applications).

The RPG islets correspond to one or more contiguous fields with the same crop bounded by easily identifiable and permanent landscape objects (e.g. road, river, forest) (Inan *et al.*, 2010). Depending on the region, the mean size of islets ranges from less than 3 ha to more than 7 ha (Figure 7b). Islets with only



one crop field (possibly with an additional fallow area) represent less than 40% to more than 70% of the total area, depending on the region (Figure 7c).



**Figure 7.** (a) Example of “Registre Parcellaire Graphique” (RPG) islets digitized by farmers on a 1:5000 orthorectified photograph; (b) Average area of islets in the 2009 RPG per district (county) in France; (c) Percentage of the total area in 2009 RPG islets covered by islets with a single crop field (possibly with an additional fallow area).

Currently, the RPG database is the most comprehensive and accurate source of data available on agricultural land use in crop and livestock farming systems throughout France (Cantelaube *et al.*, 2013). Only an anonymized and greatly simplified version of the RPG database is available for research purposes. In it, the ca. 120 categories that farmers can use to describe land use in their islets are aggregated into 28 classes.

Leenhardt *et al.* (2012a) developed a three-step method to determine crop sequences within agricultural islets based on analyzing annual RPG data. The first step determines temporal connections between islets over time by analyzing their spatial intersections. The second determines crop sequences within the islets by using algorithms that seek to identify, within each connected islet, areas of land use that recur between years, either directly or after aggregation or disaggregation of areas. These two steps determine crop sequences on a mean of 85% of the total area of RPG islets (see details in Levavasseur *et al.*, 2016). The third step interpolates these crop-sequence data to islet areas not estimated by the first two steps. The method provides data for 95-99% of the total area of RPG islets, depending on the region. To date, it has been applied to 2006-2014 (9 years) but it should be applied to each newly available annual RPG. To address the potentially large number of estimated sequences in a territory (*e.g.* several thousand in a 1000 km<sup>2</sup> territory), a typology of sequences was developed. It groups crop sequences that are considered to express the same fixed or flexible sequence and, in turn, provides more usable information about the diversity and spatial distribution of crop sequences.

The RPG and crop-sequence databases provide key data for analyzing the characteristics, diversity and spatial distribution of land use in farming systems for any type of territory in France (*e.g.* Natura 2000, watershed, administrative region). For instance, in studies performed for the French Ministry of Ecology, these databases were used to analyze (i) crop and sequence diversity on French farms and potential impacts of CAP cross-compliance rules (Fuzeau *et al.*, 2012; Allaire *et al.*, 2013) and (ii) dynamics of permanent grasslands in small agricultural regions (Faïq *et al.*, 2013). In participatory methods developed to design new spatial distributions of cropping systems, these data can be used to assess areas concerned by changes envisioned by stakeholders : *e.g.* address water deficits at the watershed level (Murgue *et al.*, 2015), or develop interactions between crop and livestock farming systems at the local level (Moraine *et al.*, 2016). Data on crop area and sequences on farms can also be used to allocate spatially other key descriptive data of farming systems. For instance, they were identified and used as spatial drivers of crop-management practices in the Aveyron River watershed, in southwestern France (Murgue *et al.*, 2014a; Murgue *et al.*, 2016). Finally, these data can be used as input data in computer models that simulate interactions between agricultural activities and the environment. For instance, in the MAELIA multi-agent

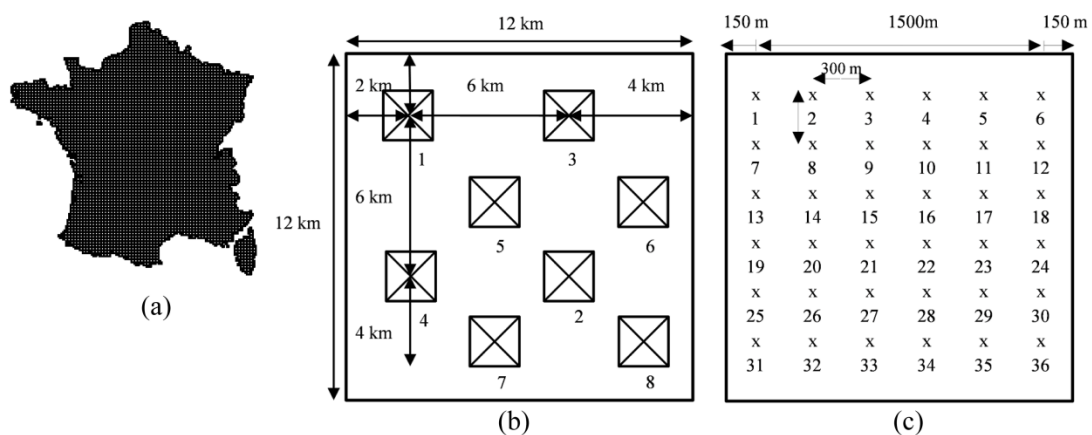
modeling and simulation platform, which simulates behavior of social-ecological systems (SES), these data are used to define the spatial structure of the agricultural landscape and to simulate spatial dynamics of land use (Therond *et al.*, 2014; Murgue *et al.*, 2014b).

Data from the simplified version of the RPG on areas concerned by agri-environmental measures and on crop sequences are accessible from the “Observatoire du Développement Rural” (ODR) platform ([https://odr.inra.fr/intranet/carto\\_joomla/](https://odr.inra.fr/intranet/carto_joomla/)), according to a variety of access conditions.

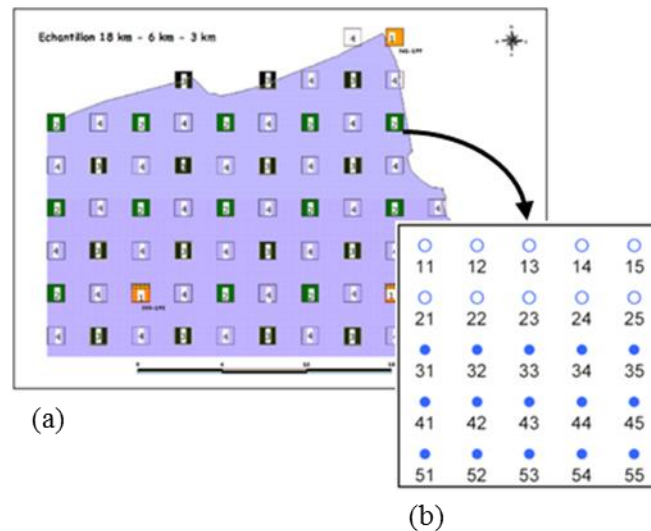
### 2.1.2. Teruti and Teruti-Lucas surveys

Teruti and Teruti-Lucas data are collected by the French Ministry of Agriculture for all of mainland France. These surveys have provided annual land-cover and land-use data since 1981 for a constant sample of observation sites. Four time series are available: 1981-1990 and 1992-2003 for the Teruti survey, and 2006-2010 and 2012-2014 for the Teruti-Lucas survey. The sample of observation sites was changed completely in 1991 and 2005. The survey was not performed in 2011. From 1981-2004, 25 classes were used to describe land use and 81 classes for land cover, 36 of which were cropland. Since 2005, the classification changed to 38 classes of land use and 88 classes of land cover, 41 of which were cropland.

Until 2010, data were collected by field observations. Since 2012, the RPG has been used to describe land cover of the sites on agricultural land. The survey follows a two-level sampling method. Before 2005, France was divided into 4700 cells of 12 km × 12 km (Figure 8a). The first sampling level consisted of selecting aerial photographs. In most regions, four out of eight aerial photographs (positions 1-4, Figure 8b) were selected within each cell. In total, 15 579 aerial photos were selected every June during the survey period. One aerial photograph covered ca. 3.24 km<sup>2</sup>. Since 2005, the main sample has been formed by intensifying the Lucas Eurostat survey. Unlike Teruti points, Teruti-Lucas points are georeferenced. The first sampling level is based on 32 498 cells, which correspond to the intersections of 3 km × 3 km cells in a regular grid (Figure 9a). Before 2005, the second sampling level was built from 36 sampling points evenly distributed (ca. 300 m apart) within the area of an aerial photograph (Figures 8b, 8c). Since 2005, each cell of the first sampling level has contained 25 evenly distributed sampling points (300 m apart) (Figure 9b). The first two lines (i.e. 10 points) constitute the final sample. Land cover or land use in France is recorded in a matrix with sampling points in rows and annual data points in columns. The corpus of land cover or land use contains 555 382 sampling points before 2005 and 322 191 points after 2005.



**Figure 8.** Diagram of the two-level sampling method of the Teruti land-cover survey from 1992-2003. (a) France was divided into 4700 cells. (b) Eight aerial photographs were taken in each cell. (c) Thirty-six sampling points were evenly distributed within each aerial photograph. One Teruti sampling point covered ca. 100 ha.



**Figure 9.** Diagram of the two-level sampling method of the Teruti-Lucas land-cover survey since 2005. (a) France is covered by regularly spaced cells. (b) Twenty-five sampling points are evenly distributed within each cell. Points 11-25 are included in the Lucas survey. One Teruti-Lucas sampling point covers ca. 178 ha in most French departments.

Since 2006, the Teruti-Lucas survey has been available on the website of the French Ministry of Agriculture (<https://stats.agriculture.gouv.fr/disar/>), with variable amounts of detail about classifications, aggregated by administrative region or at the national level. Teruti and Teruti-Lucas surveys have two main goals. The first is to analyze land-use changes in France (*e.g.* sealing of agricultural land, forest dynamics, conversion of grasslands into cropland). These land-use changes have been used, for instance, to estimate dynamics of soil carbon stocks (Martin *et al.*, 2019). The second goal, enabled by the fixed sample structure within each type of survey (*i.e.* time series), examines the annual succession of land-cover types of the areas of sampling points classified as agricultural land to establish their crop sequences. Agronomic studies were performed using these surveys to analyze spatial differentiation of crop sequences in France and its dynamics (Mignolet *et al.*, 2004; Mignolet *et al.*, 2007; Leenhardt *et al.*, 2012b; Xiao *et al.*, 2014; Xiao *et al.*, 2015). These studies also resulted in development of data-mining software that automates analysis of spatio-temporal patterns in land-use and land-cover data (Le Ber *et al.*, 2006).

### 2.1.3. Contribution of remote sensing to land-use and land-cover mapping

Temporal variations in reflectance data (or vegetation indices) can be useful for distinguishing among different vegetation types to produce land-cover or land-use maps (Waldner *et al.*, 2015; Inglada *et al.*, 2015). In 1985, the EU initiated the CORINE Land-Cover program, which inventories land cover in 44 classes. Its database is operationally available for most areas of Europe, but with a limited spatial resolution (at a scale of 1:100 000, minimum polygon size = 25 ha) and temporal repetitivity (*ca.* every 5 years). In 2016, THEIA started producing operationally a yearly land-use map of France, based on multi-temporal signatures of Sentinel-2 at a spatial resolution of 10 m. The number of land use classes (from 17 in 2016 to 23 in 2019) and temporal frequency of the releases will increase regularly. Thus, future release may allow inter-annual crop successions and forest changes to be monitored. Reprocessing, which consists of processing all data measured since the Sentinel-2 launch using the most recent version of the classification algorithm, will be performed regularly to produce consistent historical time series.

To obtain information about smaller objects (*e.g.* hedges, hedgerow networks, linear strips of woody vegetation and orchards, drainage ditches, drainage networks), optical observations at higher spatial resolution (very high resolution, *ca.* 1-2 m), such as those made by IKONOS, QuickBird, Pleiades-HR or GeoEye-1 can be processed using pattern-recognition techniques such as object-based image analysis, whose image classification approximates that of human perception by dividing the image into “image objects” (groups of contiguous pixels). Coherent small ground features can be delineated at different



scales and provide an appropriate representation of meaningful patches or ecological entities (Fauvel *et al.*, 2014). Optical data can be combined with Lidar or radar data depending on the application (Bailly *et al.*, 2001; Bargiel, 2013; Betbeder *et al.*, 2014). These methods are now operational (except for linear strips) but require specific expertise. Very-high-resolution images can be expensive, but the ISIS service of THEIA can provide Pleiades-HR observations at lower cost for research institutes.

## 2.2. Crop management

A comprehensive data set of crop-management variability at the landscape or regional level is likely the most critical point for all studies that address agriculture and the environment at these levels. The nature of the information to be collected depends on the questions that are addressed. For instance, monitoring agriculture's reliance on pesticides in a given area requires collecting details about pesticide applications in a representative subset of farms in the area. Then, analyzing potential antagonisms among pesticide use, economic profitability and environmental issues (e.g. energy consumption) would require supplementing the data on pesticide applications with many details about cropping practices, inputs and yields, to be able to calculate indicators of economic profitability and environmental impacts. In such a study, however, the need for a representative data set is less important than capturing the range of variability in cropping practices in the area. Assessing the significance of cultivated genetic diversity on the performance of farming systems would also require knowing the cultivars grown for each crop species at the farm level. Spatial comprehensiveness may become an objective if consequences of the spatial arrangement of cultivars will be considered. Field surveys at national or local levels may provide information about crop management. Networks of demonstration farms are currently being organized and are good sources of detailed information. Compiling large data sets on crop management from a variety of sources requires using dedicated information systems that share the same ontology to describe characteristics such as agricultural practices, equipment, inputs and cultivars.

### 2.2.1. Field surveys

In France, the main official source of information about agricultural practices on commercial farms comes from individual surveys called "Pratiques Culturelles" (i.e. Cropping Practices), which were initiated in 1986 by the Ministry of Agriculture and are performed every 5 years for crops and grasslands (1986, 2001, 2006, 2011 and 2017). Their initial objective was to assess consequences of public-action programs to decrease water pollution by nitrates from agricultural activities according to the EU Nitrates Directive (91/676/CEE). They were extended to other agricultural sectors, such as viticulture (in 2006), fruit trees (in 2012) and vegetables (in 2014). They were also extended to other objectives, especially evaluating the efficacy of the ECOPHYTO program, for which intermediate partial surveys on pest-management practices are performed (in 2014 for crops).

The main objective of these surveys is to characterize the cropping practices (e.g. tillage, sowing, use of inputs, harvest) of the main types of agricultural production in mainland France and overseas departments. In 2017, 14 crops were included in the survey: bread and durum wheat, barley, triticale, grain and forage maize, oilseed rape, sunflower, field pea, soybean, sugar beet, potato, temporary grasslands, permanent meadows and sugarcane. The data have been used, for instance, to calculate regional references for the level of pesticide use based on the Treatment Frequency Index (TFI) estimated for each surveyed field and averaged at the regional level for each crop (Agreste, 2013). Then, regional reference TFIs were calculated as a weighted average of all crop TFIs in each region, with the weights equal to the proportion of each crop in the region. These regional reference TFIs have been used extensively to monitor the ECOPHYTO program to identify cropping systems with low/medium/high levels of pesticide use compared to the distribution of pesticide use in each region.

Plots are sampled from the fields that applied for CAP subsidies. For each type of crop, at least 90% of the area sown nationally must be covered by the survey. In each administrative region, the French departments surveyed must cover altogether at least 85% of the area sown regionally. In each region, the cropping practices of 100-2300 fields are described, depending on the variability in yield within the region. Consequently, 1000-3000 plots are sampled at the national level for each major crop, following a procedure that aims for representativeness.

All cropping practices from the harvest of the preceding crop to harvest of the surveyed crop are collected: fallow management; primary and secondary soil tillage (date, depth and equipment); sowing (equipment, variety, sowing date and rate), mineral and organic fertilization; weed, pest and disease control (products, dates and rates); irrigation (dates and amount) and harvest (date and yield). Only general information about soil type and the plot environment is provided. Some descriptors of the cropping system (limited to the five previous years) are given: preceding crops, plowing (or not) and organic or mineral fertilization (or none). Other qualitative descriptors are mentioned, such as the existence of labels or specifications (e.g. organic farming) and the use of decision support methods. All of this information is collected directly on farms by investigators who meet with each farmer.

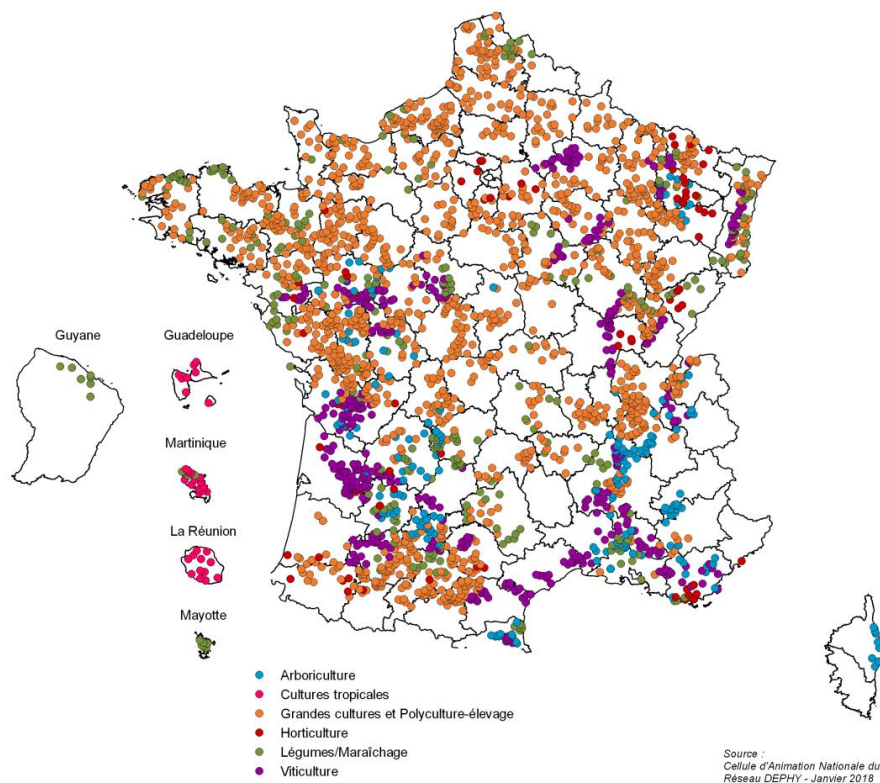
Schmidt *et al.* (2010) used 2006 data from this survey to understand drivers of pesticide use in oilseed rape (OSR), which has high herbicide and insecticide use in France. Fields from the survey were characterized by the cropping system in which OSR occurred and the crop management applied to it. Variables used to characterize cropping systems were relative frequencies of OSR, cereals and spring crops in the crop sequence and frequencies of plowing and organic fertilization. Principal component analysis followed by hierarchical clustering applied to elementary field data yielded six types of cropping strategies. The variables used for crop management were related to soil tillage, sowing and fertilization of OSR. Using the same clustering method, six types of crop management were identified. Among the 36 possible cropping systems that resulted from combining cropping strategies and crop management, 13 represented more than two-thirds of surveyed areas, which illustrates that crop management depends on the cropping strategy into which OSR is inserted. Cropping system groups differed significantly in mean TFI. High TFI (total or herbicide-only) were observed for fields where OSR was frequently grown and plowed occasionally, while OSR inserted in more diversified and frequently plowed systems resulted in lower pesticide use. The 36 types were distributed widely among regions. For instance, in the central “stony-soil belt” (Lorraine, Burgundy, Poitou-Charentes), short crop sequences with simplified soil tillage and high herbicide use predominated. A similar approach was adopted to describe cropping systems that included maize in order to support decision making of the French High Council for Biotechnologies about adoption of genetically modified cultivars (Ballot *et al.*, 2017a). Studies also used specific data from these surveys to support public decision making, such as two recent expert assessments that addressed the use of glyphosate and neonicotinoid insecticides and existing alternatives, respectively (Reboud *et al.*, 2017; Vergriette *et al.*, 2018).

Another study based on these surveys is that of Aouadi *et al.* (2015), who analyzed the influence of the farming context and environmental factors on cropping systems in the Burgundy region. They subjected ca. 800 fields from the 2006 survey to multivariate analysis and hierarchical clustering to build a typology of production situations (i.e. farming contexts) and cropping systems that differed in crop sequence and levels of pesticide and fertilizer use.

At the crop level, extension institutes perform surveys more frequently (e.g. postal surveys of OSR and sunflower by Terres Inovia every 2 years; Wagner and Quere, 2005). These data update knowledge about farmers’ current practices and how they change over time. For instance, 1200 responses were analyzed in a 2011 survey of sunflower production. As before, they have been used to build typologies of crop management systems (Sarron *et al.*, 2017) and thus differentiate recommendations depending on the system. Crop-management systems can be inferred from this type of data accessible at the field level. In a perspective of supporting public decision making, these surveys are useful for (i) capturing dynamics of cropping systems in France at the regional level and (ii) identifying mechanisms and promising avenues.

### 2.2.2. Pilot farms

The DEPHY farm network was established in 2010, when 3000 farmers volunteered to demonstrate that it was possible to reduce their pesticide use according to the ECOPHYTO program (Figure 10). Their farming systems include arable crops, vineyards, orchards, vegetables, horticulture and tropical crops. An information system (Agrosyst, Box 1) was built to ease storage and analysis of the huge amount of data collected. Although several networks of reference farms are active in several regions, the DEPHY network currently has the most farms and information collected about these practices.

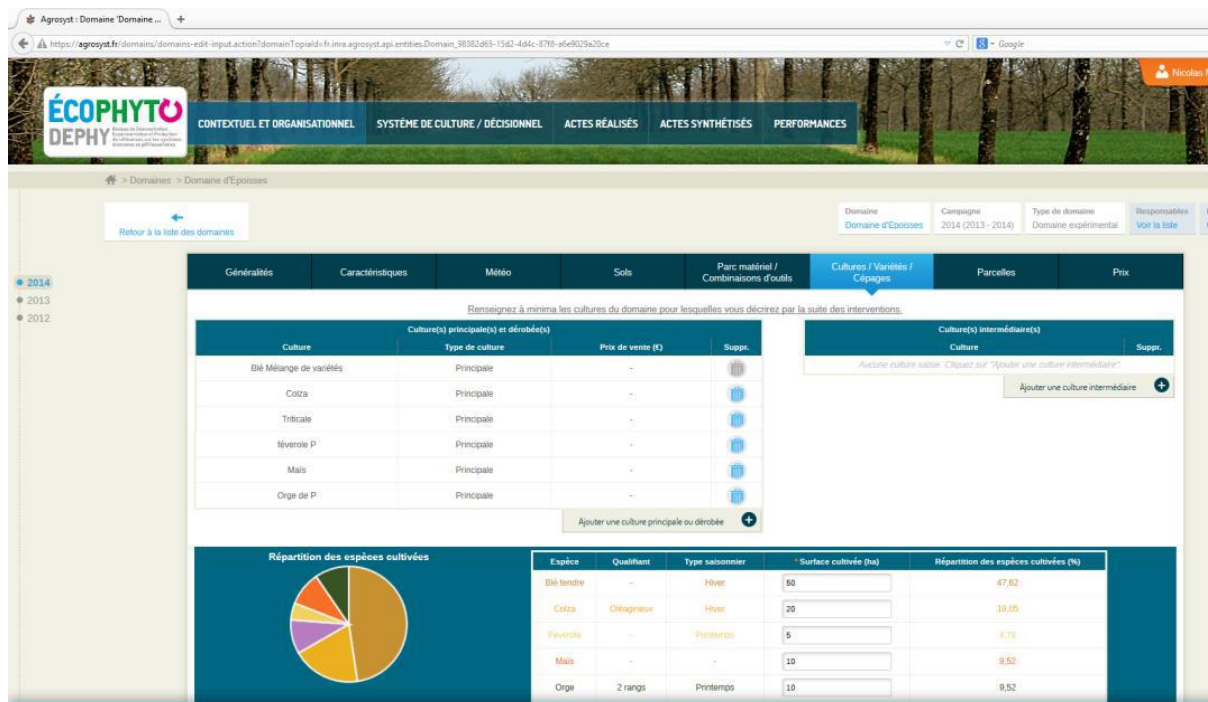


**Figure 10.** Distribution of pilot farms in the DEPHY network (2017), in which agricultural practices target a significant decrease in pesticide application (French national program ECOPHYTO) : orchards, tropical crops, field crops and mixed farming, horticultural crops, vegetables, vineyards.  
 Source: <http://agriculture.gouv.fr/quoi-de-neuf-dans-les-fermes-dephy>

The unique value of the dataset produced by a large farm network such as DEPHY comes from combining (i) a large number of cropping systems with a huge variability in cropping practices in a wide variety of production situations (e.g. soil type; climatic conditions; type of farm; livestock presence or not; ability to irrigate or not; local markets for industrial crops such as sugar beets, potatoes and other vegetables) and (ii) detailed description of the entire farming/cropping system, including crop sequences and details about crop management for each crop. Unlike the information collected by the Ministry of Agriculture (see section 2.2.1) for a wide range of farms but only once every 5 years, DEPHY does not require formulating hypotheses to build consistent crop sequences or track changes in practices.

**Box 1. Agrosyst, a web-based application to describe cropping systems**

Agrosyst is a web-based application that was developed primarily to describe the cropping systems of the DEPHY demonstration farm network and to pool the information into a single database. Currently, it can also be used for purposes outside the DEPHY network and aims to become the main tool for describing and evaluating cropping systems in France. It provides a browsing interface with software features that facilitate data entry (Figure 11). It is based on a complex database with tables that provide standards for soil types, cultivars, equipment, etc., and other data that are used to calculate key indicators of economic performance and environmental impact.



**Figure 11.** Screenshot of the Agrosyst interface: page that describes within-farm crop diversity

Farms are described with several variables for the agricultural area, the proportion of that area covered by each crop, equipment, soil types and, if present, type(s) of livestock production. The minimum spatial information is the commune, but the exact location of the farm may be recorded. The landscape environment may be described roughly at either the farm or field level (e.g. distance to the river, buffer and grass strips, hedgerows, trees), but this information is not yet precisely georeferenced. Details about crop management (i.e. sequence of practices, equipment used, inputs, yield and quality of harvested products) may be recorded either at the cropping-system level, using a synthetic approach with a spatial resolution of the farm level, or at the field level, with a finer spatial resolution. The barycenter of each field may be georeferenced, along with information about the field's area. For perennial crops, the age and spatial arrangement of orchards/vineyards, as well as grass strips between rows, may be described. Agrosyst also includes features to describe the decision model used to manage crops, for instance using a tolerance threshold for pests and weeds that may trigger pesticide application. Once a cropping system is described completely, indicators of sustainability can be calculated (although some indicators remain under development at present). The system also can record the monitoring of crop health, pests and beneficial organisms, but this feature has not been used extensively.

Recent studies have demonstrated the value of the dataset produced by the DEPHY network to gain knowledge about agriculture's reliance on pesticides (measured by TFI) and the potential to decrease it. Based on the variability in TFI for 1000 cropping systems on non-organic arable farms (0.8-16.8), Lechenet *et al.* (2016) identified clusters of production situations with contrasting levels of pesticide use. Within each type of production situation, they identified combinations of cropping-system features associated with either low or high pesticide use. This confirmed the theory of Integrated Pest Management (IPM), which asserts that combining many pest management measures with limited individual effectiveness may decrease the need for pesticides even more effectively. It also demonstrated that (i) IPM-based management strategies were not unique, (ii) different strategies could lead to low reliance on pesticides in a given type of production situation and (iii) strategies can differ significantly among production situations, indicating that there is no "one size fits all" solution to solve the problem of pesticide reliance across a large and diverse country. Finally, Lechenet *et al.* (2017) used the same dataset to study relationships between pesticide use and both productivity and profitability at the cropping-system level. They showed that decreasing pesticide use could be antagonistic with maintaining productivity or

profitability in a few production situations, but that in most situations, IPM-based strategies to decrease reliance on pesticides could be adopted without decreasing either productivity or profitability (Lechenet *et al.*, 2017). Moreover, Urruty *et al.* (2016) showed that adopting IPM-based cropping systems would tend to decrease the sensitivity of crop yield to abiotic stresses caused by the variability in climatic conditions over several years, thus increasing system robustness. Finally, the degree to which pesticide use on arable farms in the network could be decreased without any loss of profitability was estimated by simulating the adoption by each farmer of the proper management strategy already used by another farmer in the same type of production situation. These results based on detailed information at the cropping-system level for a wide range of situations at the national scale undoubtedly have great significance for farmers, advisors and policy makers.

## **B. Integrating agro-environmental data at regional and national levels: a case study**

A recent French case study is presented to illustrate the practical use and integration of available physical and management data through modeling at the regional level. It concerns water-resource management at the regional level using MAELIA.

**Background** - In future decades, water scarcity will continue to be a major constraint for human activities, particularly agriculture, in many regions of the world (Rijsberman, 2006). Although climate change is widely recognized as a key driver of water availability (Bates *et al.*, 2008; Vörösmarty *et al.*, 2000), socio-demographic, economic and technological changes can be also major drivers of hydrological droughts (March *et al.*, 2012; Moss *et al.*, 2010; Vörösmarty *et al.*, 2000), which are periods “with inadequate surface and subsurface water resources for established water uses of a given water resource management system” (Mishra and Singh, 2010). Drought depends not only on resource levels but also on water use and management systems. It emerges from interactions within and between the four main core sub-systems of a socio-ecological system (Ostrom, 2009): (i) resource systems (*e.g.* hydrological systems), (ii) resource units (*e.g.* water volume and flow), (iii) users (*e.g.* individuals and collectives that use resource units) and (iv) governance systems (*e.g.* institutions that regulate water use). In agricultural landscapes, where irrigation is the main determinant of water issues, water deficits at the watershed level result from daily site-specific interactions between farm crop-management strategies, hydrology of water resources and water-resource management (Mazzega *et al.*, 2014; Therond *et al.*, 2014). The spatial distribution of cropping systems strongly determines dynamics of the state of water resources (*e.g.* surface water, groundwater, reservoirs) (Martin *et al.*, 2016; March *et al.*, 2012; Leenhardt *et al.*, 2012b). Participatory and modeling assessment methods support and guide stakeholders in designing and assessing potential solutions to natural-resource management problems (Voinov *et al.*, 2016; Leenhardt *et al.*, 2014; Voinov and Bousquet, 2010; Bots and Daallen, 2008). One scientific challenge is to ensure that these methods represent key interactions at the spatial and temporal resolutions that make sense to address the problem at hand (Therond *et al.*, 2014).

**Integrative modeling** - MAELIA<sup>38</sup> was developed to help stakeholders address drought issues in watersheds where irrigated agriculture is the main water consumer. MAELIA represents the structure and simulates the dynamics of the four core sub-systems of investigated SES. It represents daily site-specific conditions of crop management in the fields of each farming system and states of several water resources resulting from irrigation withdrawals, hydrological flow and water-resource management. MAELIA provides scientists and stakeholders with a generic software architecture that must be used locally to address a watershed-specific water-deficit problem. It was used to help assess options for change envisioned by local stakeholders in the Aveyron watershed in a three-step participatory method: (i) co-modeling of the agricultural landscape (Murgue *et al.*, 2014a; 2016), (ii) co-design of options for change in the structure or functioning of the SES (Murgue *et al.*, 2014b; 2015) and (iii) *ex ante* assessment of effects of potential changes in water resources (Martin *et al.*, 2016).

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<sup>38</sup> <http://maelia-platform.inra.fr/>

Hydrology is modeled using equations from the Soil and Water Assessment Tool (Arnold *et al.* 1993), a semi-distributed model in which the hydrological balance is estimated and spatially allocated into “sub-watersheds” at a daily time step. These latter are subdivided into non-spatialized “hydrologic response units” that represent a unique combination of land cover, soil type and slope. They can represent variability in evapotranspiration and runoff within each sub-watershed. Equations of the generic crop model AqYield (Constantin *et al.*, 2015b) are used to simulate crop growth, soil water dynamics, run-off, percolation and crop yield at the field level. The multi-agent architecture of MAELIA represents the decision-making process of water users (including farmers) and of water-governance systems (dam managers and state services) regarding water-use restrictions.

**Data-integration approach** - Describing the databases used when applying MAELIA in France provides a good overview of the wide variety of data requested. Soils are described as finely as possible using the finest-scale soil map available (*e.g.* 1:1 000 000, see section A). Stakeholders can help improve this soil map in a participatory mapping exercise (see example in Murgue *et al.*, 2016). Sub-watersheds are delineated by analyzing BD ALTI®, the French digital elevation model (25 m × 25 m cells) developed by the French National Institute of Geographic and Forest Information (IGN). Within these sub-watersheds (mean of 25 km<sup>2</sup>) homogeneous response units are determined by analyzing the intersection of the CORINE Land-Cover Database (for non-agricultural land use, section A), the French LPIS (for agricultural land use, section A), the BD ALTI® and the soil map. SAFRAN climate data (see section A) are tagged to each sub-watershed by averaging climate data of the climate cells weighted by the proportion of their area within the watershed. Due to the small size of sub-watersheds, their climate data is tagged to all of their fields. The French LPIS provides fine-scale spatial description of the islets of fields of crop and livestock farming systems. Analyzing the annual LPIS provides information about crop areas and sequences in each islet (see section A). CORINE Land Cover is used to identify areas with other key irrigated farming systems, such as orchards. Characteristics and spatial distribution of water resources are provided by three key French georeferenced databases: (i) BD Carthage®, developed from collaboration of the five French regional water agencies and the IGN, provides data on all rivers and the largest reservoirs; (ii) BD TOPO®, developed by IGN, provides data on the spatial distribution of hill reservoirs and (iii) the groundwater database developed by the French Geological Survey. All of these databases are available for all of mainland France. Data on characteristics of small reservoirs (*e.g.* volume, nature of water use); hydraulic networks for irrigation that connect irrigated fields to water resources; regulatory zones for water-use restrictions; and domestic, industrial and agricultural withdrawal stations must be collected locally by local organizations (*e.g.* state services, irrigation collectives).

Finally, applying MAELIA to a watershed requires describing water users and management strategies. These strategies correspond to decision rules that define the conditions required to trigger technical practices (*e.g.* irrigation, water release, water-use restriction). These conditions depend on (i) the state of the biophysical (*e.g.* soil, plant, weather, water resource, maximum or minimum flows) and socio-economic (*e.g.* workforce availability, water-use restriction) contexts of the action situations and (ii) priorities among competing activities or potential resources. In MAELIA, these decision rules are represented using the typical syntax: “*IF INDICATOR OPERATOR THRESHOLD THEN ACTION ELSE ACTION*”. Simulating these decision rules represents the spatio-temporal dynamics of human activities in the watershed (*e.g.* agricultural practices in fields). Parameterizing these decision rules requires collecting data on *INDICATORS* and associated *THRESHOLD* values (see details in Murgue *et al.*, 2014; 2016). Information about strategies of dam and water-restriction managers can be collected in a few interviews with key informants (*e.g.* local state services).

Once MAELIA is applied locally, Murgue *et al.* (2015) developed a method to support local stakeholders in designing options for change. In their case study, local stakeholders envisioned two main changes to try to limit recurring water deficits in the Aveyron watershed: (i) replacing on the “warmest soils” ca. 20% of current late-flowering maize cultivars with early cultivars that would be sown ca. two weeks earlier and (ii) replacing ca. 40% of maize monocropping by a two-year sequence of maize-winter wheat in not-too-hydromorphic soils. Fine-scale description of implementation conditions provided by stakeholders helped

identify the fields concerned by changes and develop corresponding spatially explicit scenarios in the MAELIA georeferenced database. Simulation results revealed that the first option for change has little effect on water withdrawals over a 10-year simulation of the past, while the second decreases them by a mean of 4.2% (Martin *et al.*, 2016). Substantial decrease in the water deficit in this watershed seems to be possible only through significant changes in cropping and farming systems. Such important changes can be envisioned through iterative design and assessment cycles.

**Data collection strategy** - Using MAELIA to address watershed-specific water-deficit problems requires integrating a large amount of heterogeneous data. MAELIA can be used initially with raw data to start a participatory modeling process, assuming that the geodatabase will be improved over time according to future requirements and opportunities. The main challenge in this quality-improvement process may be to develop a web-based communication system to allow water users to provide data on their crop management strategies themselves (Debril and Therond, 2014). Different strategies can be used to collect this key information. Murgue *et al.* (2016) recommend first holding a participatory workshop with local agricultural experts to develop a typology of cropping systems and identify determinants of their spatial distribution (i.e. production situations), and then to survey representative farms in the production situations identified. A test of a less resource-consuming method, based only on expert interviews, is currently being evaluated (Rizzo *et al.*, 2019).

## C. Perspectives for data collection and integration

### 1. Practical aspects of using agro-environmental data: from France to Europe

**Data availability** - Data required by landscape- and territory-level agronomy for local to regional and national studies are increasingly available and benefit from higher spatial and temporal resolutions. This is particularly true for climatic and soil data. Climatic grid data are now commonly used in agronomy to study past and future impacts of climate change on cropping systems (e.g. Shelia *et al.*, 2019). Soil maps at 1:250 000 will be soon available for all of France, which will improve representation of soil diversity at watershed and regional levels (Richer de Forges *et al.*, 2019).

At the same time, climatic and soil data can be used easily at the European level with the same resolution as at the national level, since most of the exploration studies are relevant at the continental level, especially when considering climate change (Donatelli *et al.*, 2012). The ambition of the European Soil Data Centre<sup>39</sup> is to be the single reference point for and to host all relevant soil data and information at the European level, delivering freely upon request a wide range of resources, including maps and datasets. The European Climate Assessment & Dataset (ECA&D) project distributes information about changes in weather and climate extremes, as well as the daily dataset (E-OBS) needed to monitor and analyze these trends<sup>40</sup>. E-OBS is a daily gridded observational dataset based on ECA&D information and originally developed and updated in the ENSEMBLES (EU-FP6) and EURO4M (EU-FP7) projects. The full dataset covers 1950-2015 and contains 43 055 series of observations for 12 variables at 10 571 meteorological stations throughout Europe and the Mediterranean. Overall, 76% of these daily series can be downloaded from the ECA&D website for non-commercial research and education.

Spatial representations based on geographic information systems are increasingly preferred to station-based approaches in regional and national studies. Land-cover maps are derived from various sources (see Section A) but unfortunately are not produced annually (e.g. CORINE Land Cover) or have restricted access (e.g. RPG, Teruti-Lucas). New remote-sensing products (e.g. Sentinel-2) could likely fill this gap routinely at the field level in coming years or be complementary (Bontemps *et al.*, 2015).

Cropping-practice data are not available each year, however, and only a small proportion of farms in France are investigated every 5 years. This information is necessary for observing major trends in farm practices and estimating environmental and economic performances of cropping and farming systems.

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<sup>39</sup> <http://esdac.jrc.ec.europa.eu/>

<sup>40</sup> [https://surfobs.climate.copernicus.eu/dataaccess/access\\_eobs.php](https://surfobs.climate.copernicus.eu/dataaccess/access_eobs.php)



Since climatic conditions may influence the practices observed during a given year, efforts should be concentrated on increasing the frequency and spatial extent of surveys of agricultural practices and collecting the decision rules behind crop-management practices. If not possible, sampling of the spatio-temporal variability in the practices should be optimized by combining multiple data sources and clustering these data to increase the representativeness of the data from surveys. However, this diversity and heterogeneity of information from multiple sources and stakeholders could also be difficult to manage and integrate.

To develop a fine-scale geographic information system for cropping systems in France, new developments underway at INRAE aim to supplement the French LPIS and associated crop-sequence data (section A) with data on cropping practices from either the “Pratiques Culturelles” surveys of the Ministry of Agriculture or other surveys (e.g. by French technical Institutes) (e.g. Syppre project; L’Herbier *et al.*, 2016). Combined with crop models, satellite imagery could supply additional information about farm practices (e.g. sowing date, tillage, irrigation) and soil data (Atzberger, 2013).

*Data access* - Soil and climate data are now freely available for research goals at both national (INRAE, Météo-France) and European levels (EU Joint Research Centre). However, land-use and cropping-practice data, which come from surveys performed by the French Ministry of Agriculture or declarations of farmers who applied for CAP subsidies, are less easily available. While summary data are freely available (e.g. at departmental or regional levels), anonymized individual data are available only for consultation (but not downloading) through a secure data-access center (“Centre d’Accès Sécurisé à Distance”) after signing an agreement with the French Committee on Statistical Confidentiality. For this reason, combining individual information about farms and farmers from different sources is strongly restricted. This was reinforced by the recent General Data Protection Regulation of the EU (no. 2016/679), which limits use of personal data even more.

Collecting data using public funds will probably not be sustainable in the future. Because of technological progress, data on cropping practices could be entered directly by farmers on web services, through participatory approaches. Farmers could be encouraged to benefit from analysis based on the entire dataset and/or recommendations built from their own data and decision support systems. This approach is already offered to members of farming cooperatives through commercial decision support systems. For instance, a single template is used to collect information about cropping practices to calculate optimal fertilizer rates. This template could be used to support a wider range of decisions. Living labs built to test and refine technical or organizational innovations in agriculture should be based on such data sharing. In addition, farmers who receive public subsidies increasingly have to justify their agricultural practices, especially in environmentally vulnerable zones, and this will provide another source of data.

*Data interoperability* - As mentioned, it is impossible to match the wide variety of information available at the farm level for reasons of confidentiality and data resolution (Janssens *et al.*, 2009). Therefore, most studies use clusters of cropping practices at the regional level, with difficulties combining physical, agronomic and economic information completely at farm or field levels. However, soil and climatic data are now routinely matched using climatic grids (8 km × 8 km cells at the national level, 25 km × 25 km cells at the European level). The detailed description of farming and cropping systems or natural resources often requires supplementing available databases with local expert knowledge (e.g. on crop management practices). The future challenge will be to develop sound methods to integrate and hybridize data from available generic databases and local experts to develop a consistent description of the territory investigated (Murgue *et al.*, 2016; Rizzo *et al.*, 2019).

## **2. Additional agro-environmental data to collect and integrate in the near future**

*Biodiversity data* - Many networks produce valuable information about biodiversity and its dynamics over time, but no example of full integration of biotic and abiotic data at regional or national levels was found in the literature. Consequently, no maps of the resulting incidence or crop damage of changes in cropping systems can be produced routinely. One reason is likely the lack of crop models that combine both biotic and abiotic factors, but also insufficient coverage of a country by observation and sampling networks. New



sensors are being developed to capture spores and pollen in the atmosphere and analyze their composition and concentration, thus improving predictions of future epidemics of plants. Recently, Terrat *et al.* (2017) used the RMQS, which covers all of France with 2173 sites, to describe the taxonomic richness of soil microbiota throughout France and relate it to soil characteristics, climatic conditions, geomorphology, and land use.

*Ecosystem services* - While relationships between farming practices/systems, biodiversity (planned, associated and landscape heterogeneity) and ecosystem services to farmers and society still require large amounts of research, fine-scale mapping of ecosystem services is advancing greatly (Tibi and Therond, 2018). This mapping allows the spatial configuration of ecosystem services to be analyzed and in turn can support land-use planning and ecosystem management (Malinga *et al.*, 2015; Martínez-Harms and Balvanera, 2012). In the EU, the “Mapping and Assessment of Ecosystems and their Services” program asks Member States to implement a National Ecosystem Assessment (MAES, 2014). In France, it was managed by the Ministry of Ecology and called “Evaluation Française des Ecosystèmes et des Services Écosystémiques” (EFESE)<sup>41</sup>. From 2014-2017, INRAE was responsible for identifying and evaluating at a fine scale ecosystem services provided by French agroecosystems. This important study was based on integrating (i) data on soil, climate, crop sequences, crop and grassland management practices and semi-natural habitats and (ii) landscape composition and configuration indicators and crop and grassland modeling (Therond *et al.*, 2017; Tibi and Therond, 2018).

### **3. Concluding remarks**

Collecting and integrating georeferenced data as inputs for models used in landscape agronomy and integrated assessment has continued to progress, especially with the advent of remote sensing and, more generally, the big-data and open-source movements. However, integrating physical characterization and human activities (e.g. socio-economic performances, work schedules) remains a methodological challenge in agriculture. It depends in part on political decisions about data access, which increasingly require open-source licenses for data collected with public funds while increasing the protection of personal data.

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<sup>41</sup> <https://www.inrae.fr/sites/default/files/pdf/etude-efese-resume-en-anglais-1.pdf>

## References

- Agerberg, J., Cellier, V., Cariolle, M., Gouache, D., Aubertot, J.-N. (2011) Rapport final de l'étude de faisabilité du développement et de la valorisation d'une base de données sur l'évolution des pressions biotiques dans les parcelles agricoles. <https://www.gchp2e.fr/Actions-thematiques/Protection-integree/Developpement-et-de-la-valorisation-d-une-base-de-donnees-sur-les-pressions-biotiques>
- Agreste (2013). Les indicateurs de fréquence de traitement (IFT) en 2011. AGRESTE Les Dossiers n°18, 5-9.
- Allaire, G., Fuzeau, V., Therond, O. (2013). La diversité des cultures et l'écologisation de la Politique Agricole Commune. INRA Sciences Sociales - Etudes - Recherches en économie et sociologie rurale, n° 1-2/2013, 7 p.
- Al-Yaari, A., Wigneron, J.P., Ducharne, A. Kerr, Y., De Lannoy, G., Wagner, W., Al Bitar, A., Dorigo, W., Rodriguez, N., Richaume, P., Mialon, A. (2014). Global-scale evaluation of two satellite-based passive (SMOS) and active (ASCAT) microwave soil moisture retrievals using MERRA-land soil moisture estimates, *Remote Sens Env* 152: 614–626.
- Antoni, V., Arrouays, D., Bispo, A., Brossard, M., Le Bas, C., Stengel, P., Villanneau, E. (Coords), Baize, D., Barriuso Benito, E., Blanca, Y., Boulonne, L., Briand, O., Cabidoche, Y.-M., Caria, G., Chéry, P., Cluzeau, D., Cousin, I., Couturier, A., Decaëns, T., Denoroy, P., Dequiedt, S., Derrière, N., Desbourdes, S., Dupuits, E., Fardeau, J.-C., Feix, I., Gabrielle, B., Gibaud, C., Guernion, M., Hartmann, A., Hénault, C., Jamagne, M., Jolivet, C., Laroche, B., Le Martret, H., Lehmann, S., Lemerrier, B., Lucas, S., Malet, J.-P., Martin, M., Massad, R. S., Miskovsky, J.-C., Moulin, J., Morard, V., Nazaret, S., Pasquier, C., Péres, G., Perrin, J.-L., Perrin, P., Ranjard, L., Richard, G., Richer de Forges, A., Roger-Estrade, J., Saby, N., Sauter, J., Schnebelen, N., Vibert, M.-A., Walter, C. (2011). L'état des sols de France. Paris, France : Groupement d'Intérêt Scientifique sur les Sols, 188 p.
- Aouadi, N., Aubertot, J.N., Caneill, J., Munier-Jolain, N. (2015). Analyzing the impact of the farming context and environmental factors on cropping systems: A regional case study in Burgundy. *Eur J Agron* 66: 21–29.
- Arnold, J.G., Allen, P.M., Bernhardt, G. (1993). A comprehensive surface-groundwater flow model. *J Hydrol* 142: 47-69.
- Arrouays, D., Jolivet, C., Boulonne, L., Bodineau, G., Ratié, C., Saby, N., Grolleau, E. (2003). Le Réseau de Mesures de la Qualité des Sols de France (RMQS). *Etude et Gestion des Sols*, 10 (4), 241-250.
- Asner, G.P., Clark, J.K., Mascaró, J., Galindo García, G.A., Chadwick, K.D., Navarette Encinales, D.A., Paez-Acosta, G., Cabrera Montenegro, E., Kennedy-Bowdoin, T., Duque, A., Balaji, A., von Hildebrand, P., Maatoug, L., Phillips Bernal, J.F., Yepes Quintero, A.P., Knapp, D.E., García Dávila, M.C., Jacobson, J., Ordóñez, M.F. (2012). High-resolution mapping of forest carbon stocks in the Colombian Amazon. *Biogeosciences* 9: 2683-2696.
- Atzberger, C. (2013). Advances in remote sensing of agriculture: context description, existing operational monitoring systems and major information needs. *Remote Sens.* 5: 949-981.
- Bailly, J.S., Lagacherie, P., Millier, C., Puecha, C., Kosuth, P. (2008). Agrarian landscapes linear features detection from LiDAR: application to artificial drainage networks. *Int J Remote Sens* 29: 3489–3508.
- Ballot R., Chauvel B., Guichard L. How corn is cultivated in France? A cropping systems typology to support public decision making on genetically modified cultivars (2017a). In: Managing global resources for a secure future. International ASA, CSSA, and SSSA Annual Meeting, Tampa (FL), Oct. 22-25.
- Ballot R., Chauvel B., Guichard L. (2017b). Comment est cultivé le maïs en France aujourd'hui ? *Phytoma* n°706, pp 43-47
- Baret, F., Weiss, M., Lacaze, R., Camacho, F., Makhmara, H., Pacholczyk, P., Smets, B. (2013). GEOV1: LAI, FAPAR Essential Climate Variables and FCOVER global time series capitalizing over existing products. Part1: Principles of development and production. *Remote Sens Env* 137: 299-309.
- Bargiel, D. (2013). Capabilities of high resolution satellite radar for the detection of semi-natural habitat structures and grasslands in agricultural landscapes, *Ecol Inform* 13: 9–16.

- Bates, B.C., Kundzewicz, Z.W., Wu, S., Palutikof, J.-P. (Eds.), (2008). *Climate Change and Water*. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 p.
- Benoît, M., Rizzo, D., Marraccini, E., Moonen, A.C., Galli, M., Lardon, S., Rapey, H., Thenail, C., Bonari, E. (2012) Landscape agronomy: a new field for addressing agricultural landscape dynamics. *Landscape Ecol.* 27: 1385–1394.
- Betbeder, J., Nabucet, J., Pottier, E., Baudry, J., Corgne, S., Hubert-Moy, L. (2014). Detection and characterization of hedgerows using TerraSAR-X imagery. *Remote Sens* 6: 3752-3769.
- Bockstaller C., Guichard L., Makowski D., Aveline A., Girardin P., Plantureux S. (2008). Agrienvironmental indicators to assess cropping and farming systems. A review. *Agron Sustain Dev* 28: 139-149.
- Boiffin, J., Benoit, M., Le Bail, M., Papy, F., Stengel, P. (2014). Agronomie, espace, territoire : travailler “pour et sur” le développement territorial, un enjeu pour l'agronomie. *Cah Agric* 23: 72-83.
- Boillot, M., Sauzet, G., Pelzer, E., Penaud, A., Pic, E., Carpezat, J., Pinochet, X., Aubertot, J.-N., Bousset, L., Jeuffroy, M.-H. (2008). Sustainable management of rapeseed blackleg by modelling and monitoring of a pilot production area. *ENDURE International Conference 2008, Diversifying crop protection, La Grande-Motte (France), 12-15 October 2008, 4 p., O.44*
- Bontemps, S., Arias M., Cara, C., Dedieu, G., Guzzonato, E., Hagolle, O., Inglada, J., Matton, N., Morin, D., Popescu, R., Rabaute, T., Savinaud, M., Sepulcre, G., Valero, S., Ahmad, I., Begue, A., Wu, B., de Aballeyra, D., Diarra, A., Dupuy, S., French, A., Akhtar, I., Kussul, N., Lebourgeois, V., Le Page, M., Newby, T., Savin, I., Veron, S.R, Koetz, B., Defourny, P. (2015). Building a data set over 12 globally distributed sites to support the development of agriculture monitoring applications with Sentinel-2. *Remote Sensing* 7 (12), 16062-16090.
- Bordat, A., Debaeke, P., Dechamp-Guillaume, G., Mestries, E., Seassau, C., Vincourt, P. (2011). *Phoma et dessèchement précoce du tournesol. Les points techniques du CETIOM*, Paris, 86 p.
- Borgy, B. (2011). *Dynamique et assemblage des communautés adventices: approche par modélisation statistique*, Ph Thesis, Univ Dijon
- Bories, N., Samalens, J.-C., Guyon, D., Breda, N., Wigner, J.-P. (2012). Monitoring pine defoliation due to the processionary moth at regional scale from MODIS time series, *IEEE International Geoscience and Remote Sensing Symposium, IGARSS'2012, 22-27 July 2012, Munich, Germany*.
- Bornand, M. (1997). *Connaissance et suivi de la qualité des sols en France. Etat des lieux, enjeux, besoin en données, proposition pour une gestion raisonnée de la ressource en sol. Rapport d'expertise du ministère de l'agriculture, du ministère de l'environnement et de l'Inra*. 176p.
- Bots, P.W.G., Daalen, A.C. E. Van. (2008). Participatory model construction and model use in natural resource management : a framework for reflection. *Syst Pract Action Res* 21: 389–407.
- Brisson, N., Levraut, F. (2010). *Changement climatique, agriculture et forêt en France: simulations d'impacts sur les principales espèces, Livre Vert du projet CLIMATOR (2007-2010)*. INRA, ANR, ADEME, 336 p.
- Cantelaube, P., Carles, M. (2015). Le registre parcellaire graphique : des données géographiques pour décrire la couverture du sol agricole. *Cahier des Techniques de l'INRA, N° spécial GéoExpé*, p. 58-64.
- Caubel, J., Garcia de Cortazar-Atauri, I., Launay, M., de Noblet-Ducoudré, N., Huard, F., Bertuzzi, P., Graux, A.-I. (2015). Broadening the scope for ecoclimatic indicators to assess crop climate suitability according to ecophysiological, technical and quality criteria. *Agr Forest Meteorol* 207: 94–106.
- Constantin, J., Le Bas, C., Justes, E. (2015a). Large-scale assessment of optimal emergence and destruction dates for cover crops to reduce nitrate leaching in temperate conditions using the STICS soil – crop model. *Eur J Agron* 69: 75–87.
- Constantin, J., Willaume, M., Murgue, C., Lacroix, B., Therond, O. (2015b). The soil-crop models STICS and AqYield predict yield and soil water content for irrigated crops equally well with limited data. *Agr Forest Meteorol* 206: 55-68.
- Debril, T., Therond, O. (2012). Les difficultés associées à la gestion quantitative de l'eau et à la mise en œuvre de la réforme des volumes prélevables : le cas du bassin Adour-Garonne. *Agronomie, Environnement et Sociétés* 2 (2), 127-138.
- Delmas, M., Saby, N., Arrouays, D., Dupas, R., Lemerrier, B., Pellerin, S., Gascuel-Oudou, C. (2015). Explaining and mapping total phosphorus content in French topsoils. *Soil Use Manage* 31: 259-269.

- Délos, M., Hervieu, F., Folcher, L., Micoud, A., Eychenne, N. (2006). La «Biovigilance», des OGM au général. Exemple du suivi des grandes cultures en France. *Phytoma-LDV* 589, 44-48.
- Déqué M. (2007). Frequency of precipitation and temperature extremes over France in an anthropogenic scenario: Model results and statistical correction according to observed values. *Global Planet Change* 57: 16-26.
- Dequiedt, S., Saby, N., Lelievre, M., Jolivet, C., Thioulouse, J., Toutain, B., Arrouays, D., Bispo, A., Lemanceau, P., Ranjard, L. (2011). Biogeographical patterns of soil molecular microbial biomass as influenced by soil characteristics and management. *Global Ecol Biogeogr* 20: 641-652.
- Donatelli M., Duveiller G., Fumagalli D., Srivastava A., Zucchini A., Angileri V., Fasbender D., Loudjani P., Kay S., Juskevicius V., Toth T., Haastrup P., M'barek R., Espinosa M., Ciaian P., Niemeyer S. (2012). Assessing agriculture vulnerabilities for the design of effective measures for adaption to climate change (AVEMAC project). European Union, Joint Research Centre, doi: 10.2788/16181
- Duigou, N., Baize, D., Bispo, A. (2011). Utilisation de la base de données BDETM pour obtenir des valeurs de références locales en Éléments Traces Métalliques. Cas de la région Centre. *Etude et Gestion des Sols* 18 (2), 91-108.
- Durandeau, S., Gabrielle, B., Godard, C., Jayet, P.-A., Le Bas, C. (2010). Coupling biophysical and micro-economic models to assess the effect of mitigation measures on greenhouse gas emissions from agriculture. *Clim Change* 98: 51-73.
- European Soil Database 2.0 (2004). European Commission and the European Soil Bureau Network, CD-ROM, EUR 19945 EN.
- Ewert, F., Van Ittersum, M. K., Bezlepkina, I., Therond, O., Andersen, E., Belhouchette, H., Bockstaller, C., Brouwer, F., Heckeley, T., Janssen, S., Knapen, R., Kuiper, M., Louhichi, K., Alkan Olsson, J., Turpin, N., Wery, J., Wien, J.E., Wolf, J. (2009). A methodology for enhanced flexibility of integrated assessment in agriculture. *Environ Sci Policy* 12, 546-561
- Ewert, F., van Ittersum, M.K., Heckeley, T., Therond, O., Bezlepkina, I., Andersen, E. (2011). Scale changes and model linking methods for integrated assessment of agri-environmental systems. *Agric Ecosys Env* 142: 6-17.
- Faïq, C., Fuzeau, V., Cahuzac, E., Allaire, G., Bortzmeyer, M., Therond, O. (2013). Les prairies permanentes : évolution des surfaces en France. Analyse à travers le Registre Parcellaire Graphique. Commissariat Général au Développement Durable, Coll. Études et documents, n°96, 18 p.
- Fauvel, M., Planque C., Sheeren D., Dalla M (2014). Télédétection des éléments semi-naturels: utilisation des données Pléiades pour la détection des haies. *Revue Française de Photogrammétrie et de Télédétection* 208: 111-116.
- Fieuzal, R., Duchemin, B., Jarlan, L., Zribi, M., Baup, F., Merlin, O., Hagolle, O., Garatuza-Payan, J. (2011). Combined use of optical and radar satellite data for the monitoring of irrigation and soil moisture of wheat crops. *Hydrol Earth Sys Sc* 15: 1117-1129.
- Fieuzal, R., Baup, F., Marais-Sicre, C. (2013). Monitoring wheat and rapeseed by using synchronous optical and radar satellite data - from temporal signatures to crop parameters estimation. *Adv Remote Sens* 2: 162-180.
- Fried, G. (2007). Variations spatiales et temporelles des communautés adventices des cultures annuelles en France. Ph.D. thesis. Dijon University, France.
- Fried, G., Reboud, X., Gasquez, J. (2007). Le réseau "Biovigilance flore" : présentation du dispositif et synthèse des premiers résultats. *Annales XX<sup>ème</sup> conférence du COLUMA : journées internationales sur la lutte contre les mauvaises herbes*, Dijon, France. p 315-325.
- Fuzeau, V., Dubois, G., Therond, O., Allaire, G. (2012). Diversification des cultures dans l'agriculture française état des lieux et dispositifs d'accompagnement. Commissariat Général au Développement Durable, Coll. Études et documents, n°67, 20 p.
- Grolleau, E., Bargeot, L., Chafchafi, A., Hardy, R., Doux, J., Beaudou, A., Le Martret, H., Lacassin, J.C., Fort, J.L., Falipou, P., Arrouays, D. (2004). Le système d'information national sur les sols: DONESOL et les outils associés. *Etude et Gestion des Sols* 11, 255-269.

- Guyon, D., Guillot M., Vitasse Y., Cardot H., Hagolle O., Delzon S., Wigneron J.-P. (2011). Monitoring elevation variations in leaf phenology of deciduous broadleaf forests from SPOT/VEGETATION time-series. *Remote Sens Environ* 115: 615-627.
- Hagolle, O., Huc, M., Villa Pascual, D., Dedieu, G. (2015). A multi-temporal and multi-spectral method to estimate aerosol optical thickness over land, for the atmospheric correction of FormoSat-2, LandSat, VENUS and Sentinel-2 images. *Remote Sens* 7: 2668-2691.
- Huard, F. (2011). Changement climatique et gradient thermique en montagne : une approche pour reconstituer la température le long d'un versant du Briançonnais. Actes du XXIV<sup>ème</sup> Colloque de l'Association Internationale de Climatologie, Rovereto, 327-332.
- Inan, H. I., Sagris, V., Devos, W., Milenov, P., van Oosterom, P., Zevenbergen, J. (2010). Data model for the collaboration between land administration systems and agricultural land parcel identification systems. *J Environ Manage* 91: 2440-2454.
- Inglada, J., Arias, M., Tardy, B., Hagolle, O., Valero, S., Morin, D., Dedieu, G., Sepulcre, G., Bontemps, S., Defourny, P., Koetz, B. (2015). Assessment of an operational system for crop type map production using high temporal and spatial resolution satellite optical imagery. *Remote Sens* 7: 12356-12379.
- Jakeman, A. J., Letcher, R. A. (2003). Integrated assessment and modelling : features, principles and examples for catchment management. *Environ Modell Softw* 18: 491-501.
- Janssen, S., Andersen, E., Athanasiadis, I.N., van Ittersum, M.K. (2009). A database for integrated assessment of European agricultural systems. *Env. Sci. Policy* 12: 573-587.
- Jiguet, F., Devictor, V., Julliard, R., Couvet, D. (2012). French citizens monitoring ordinary birds provide tools for conservation and ecological sciences. *Acta Oecol* 44: 58-66.
- Justes, E., Beaudoin, N., Bertuzzi, P., Charles, R., Constantin, J., Dürr, C., Hermon, C., Joannon, A., Le Bas, C., Mary, B., Mignolet, C., Montfort, F., Ruiz, L., Sarthou, J.-P., Souchère, V., Tournebize, J., Savini, I., Réchauchère, O. (2012). The use of cover crops to reduce nitrate leaching. Effect on the water and nitrogen balance and other ecosystem services, in: *The International Fertiliser Society Meeting*. Cambridge, p. 4-43.
- Laroche, B., Richer de Forges, A., Leménager, S., Arrouays, D., Schnebelen, N., Eimberck, M., Toutain, B., Lehmann, S., Tientcheu Nguenkam, M.-E., Héliès, F., Chenu, J.-P., Parot, S., Desbourdes, S., Girot, G., Voltz, M., Bardy, M. (2014). Le programme Inventaire Gestion Conservation des Sols de France : volet Référentiel Régional Pédologique. *Etude et Gestion des Sols* 21, 125-140.
- Le Ber, F., Benoît, M., Schott, C., Mari, J.F., Mignolet, C. (2006). Studying crop sequences with CARROTAGE, a HMM-based data mining software. *Ecol Mod* 191: 170-185.
- Lechenet, M., Makowski, D., Py, G., Munier-Jolain, N.M. (2016) Profiling farming management strategies with contrasting pesticide use in France. *Agric Syst* 149: 40-53.
- Lechenet, M., Dessain, F., Py, G., Makowski, D., Munier-Jolain, N.M. (2017). Reducing pesticide use while preserving crop productivity and profitability on arable farms. *Nature Plants* 3, 17008.
- Leenhardt, D., Angevin, F., Biarnes, A., Colbach, N., Mignolet, C. (2010). Describing and locating cropping systems on a regional scale. A review. *Agron Sustain Dev* 30: 131-138.
- Leenhardt, D., Therond, O., Mignolet, C. (2012a). Quelle représentation des systèmes de culture pour la gestion de l'eau sur un grand territoire ? *Agronomie, Environnement et Sociétés* 2: 77-89.
- Leenhardt, D., Therond, O., Cordier, M.-O., Gascuel-Oudou, C., Reynaud, A., Durand, P., Bergez, J.-E., Clavel, L., Masson, V., Moreau, P. (2012b). A generic framework for scenario exercises using models applied to water-resource management. *Environ Modell Softw* 37: 125-133.
- Lemerrier, B., Gaudin, L., Walter, C., Aurousseau, P., Arrouays, D., Schwartz, C., Saby, N., Follain, S., Abrassart, J. (2008). Soil phosphorus monitoring at the regional level by means of a soil test database. *Soil Use Manage* 24: 131-138.
- Levavasseur, F., Martin, P., Bouty, C., Barbottin, A., Bretagnolle, V., Therond, O., Scheurer, O., Piskiewicz, N. (2016). RPG Explorer: a new tool to ease the analysis of agricultural landscape dynamics with the Land Parcel Identification System. *Comput. Electron. Agric* 127: 541-552.
- L'Herbier, C., Wissocq, A., Lecompte, V., Wagner, D. 2016. Enquête sur les pratiques agricoles : mention bien mais peut encore mieux faire. *Persp agric* 433: 28-30.

- MAES (2014). Mapping and Assessment of Ecosystems and their Services. Indicators for ecosystem assessments under Action 5 of the EU Biodiversity Strategy to 2020. 2nd Report – Final, February 2014. Publications office of the European Union, Luxembourg. 81p.
- Makowski, D., Nesme, T., Papy, F., Doré, T. (2014). Global agronomy, a new field of research. A review. *Agron Sustain Dev* 34: 293-307.
- Malinga, R., Gordon, L.J., Jewitt, G., Lindborg, R. (2015). Mapping ecosystem services across scales and continents – A review. *Ecosyst Serv* 13: 1–7.
- March, H., Therond, O., Leenhardt, D. (2012). Water futures: Reviewing water-scenario analyses through an original interpretative framework. *Ecol Econ* 82: 126–137.
- Martin, E., Gascoïn, S., Grusson, Y., Murgue, C., Bardeau, M., Anctil, F., Ferrant, S., Lardy, R., Le Moigne, P., Leenhardt, D., Rivalland, V., Sánchez Pérez, J.M., Sauvage, S., Therond, O. (2016). Hydrological modelling in highly anthropized river basins: examples from the Garonne basin. *Surv Geophys* 37: 223-247.
- Martin, M., Wattenbach, M., Smith, P., Meersmans, J., Jolivet, C., Boulonne, L., Arrouays, D. (2011a). Spatial distribution of soil organic carbon stocks in France. *Biogeosciences* 8 (5): 1053-1065.
- Martin, M., Sierra, J., Delannoy, D., Ripoche, D., Arrouays, D., Brisson, N. (2011b). Long term response of two models of soils organic carbon dynamics over a wide range of agro-pedo-climatic conditions. International Symposium on Soil Organic Matter, Organic matter dynamics - from soils to oceans, Leuven, 11-14 July 2011.
- Martin, M., Dimassi, B., Millet, F., Picaud, C., Bounoua, E.-M., Bardy, M., Bispo, A., Boulonne, L., Bouthier, A., Duparque, A., Eglin, T., Guenet, B., Huard, F., Mary, B., Mathias, E., Mignolet, C., Robert, C., Saby, N., Sagot, S., Schott, C., Toutain, B., Trochard, R. (2019). ***Méthodes de comptabilisation du stockage de carbone organique des sols sous l'effet des pratiques culturales (CSopra)***. Ademe, 69p.
- Martínez-Harms, M.J., Balvanera, P. (2012). Methods for mapping ecosystem service supply: a review. *Int. J. Biodivers. Sci. Ecosyst. Serv. Manage* 8: 17–25.
- Mazzege, P., Therond, O., Debril, T., March, H., Sibertin-Blanc, C., Lardy, R., Sant'Ana, D. (2014). Critical multi-scale governance issues of the integrated modeling: example of the low-water management in the Adour-Garonne basin (France). *J Hydrol* 519: 2515-2526.
- Mignolet, C., Schott, C., Benoît, M. (2004). Spatial dynamics of agricultural practices on a basin territory: a retrospective study to implement models simulating nitrate flow. The case of the Seine basin. *Agronomie* 24: 219-236.
- Mignolet, C., Schott, C., Benoît, M. (2007). Spatial dynamics of farming practices in the Seine basin: Methods for agronomic approaches on a regional scale. In: Billen G., Garnier J., Mouchel J.M., Human activity and material fluxes in a regional river basin: The Seine River watershed. *Seine Special Issue, Sci Total Environ* 375: 13-32.
- Mishra, A.K, Singh, V.P. (2010) A review of drought concepts. *J Hydrol* 391: 202-216.
- Monteith, J.L. (1965). Evaporation and environment. *Symp Soc Exp Biol* 19: 205–234.
- Moraine, M., Grimaldi, J., Murgue, C., Therond, O. (2016). Co-design and assessment of cropping systems for developing crop-livestock integration at the territory level. *Agric. Syst.* 147: 87-97
- Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P., Wilbanks, T.J. (2010) The next generation of scenarios for climate change research and assessment. *Nature* 463: 747-756
- Mulder, V.L., Lacoste, M., Richer de Forges, A., Martin P., Arrouays, D. (2016). National versus global modelling the 3D distribution of soil organic carbon in mainland France. *Geoderma* 263: 16-34.
- Murgue, C., Lardy, R., Vavasseur, V., Leenhardt, D., Therond, O. (2014a). Fine spatio-temporal simulation of cropping and farming systems effects on irrigation withdrawal dynamics within a river basin. D. P. Ames, N. W.T. Quinn, A. E. Rizzoli (Eds.). 7th Int. Congress on Env. Modelling and Software (iEMSs), San Diego, CA, USA, 8 p.
- Murgue, C., Therond, O., Leenhardt, D. (2014b). Agricultural viability in a water-deficit basin: can participatory modelling and design activities trigger collaboration between water management and agriculture stakeholders? H. Schobert, M.-C. Riecher, H. Fischer, T. Aenis, A. Knierim (Eds), Farming

- system facing global challenges: capacities and strategies. 11th European IFSA Symposium, April 1-4, 2014, Berlin, Germany.
- Murgue, C., Therond, O., Leenhardt, D. (2015). Towards sustainable water and agricultural land management: participatory design of spatial distributions of cropping systems in a water-deficit basin. *Land Use Policy* 45: 52-63.
- Murgue, C., Therond, O., Leenhardt, D. (2016). Hybridizing local and generic information to model cropping system spatial distribution in an agricultural landscape. *Land Use Policy* 54: 339-354.
- Nemani, R., Keeling, C.D., Hashimoto, H., Jolly, W. M., Piper, S. C., Tucker, C. J., Myneni, R.B., Running S.W. (2003). Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science* 300: 1560-1563.
- Orton, T., Saby, N., Arrouays, D., Walter, C., Lemerrier, B., Schvartz, C., Lark, R. (2012). Spatial prediction of soil organic carbon from data on large and variable spatial supports. II. Mapping temporal change. *Environmetrics* 23: 148-161.
- Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science* 325: 419-422.
- Pappalardo, M, Lévêque, A, Malfait, G. (2010). Données de synthèse sur la biodiversité. Commissariat général au développement durable, Service de l'observation et des statistiques, Collection RéférenceS, 88 p.
- Penman, H.L. (1956). Evaporation: An introductory survey. *Neth J Agric Sci* 4: 9-29.
- Reboud X. *et al*, 2017. Usages et alternatives au glyphosate dans l'agriculture française. Rapport Inra à la saisine Ref TR507024, 85 p.
- Richer de Forges, A., Baffet, M., Berger, C., Coste, S., Courbe, C., Jalabert, S., Lacassin, J.-C., Maillant, S., Michel, F., Moulin, J., Party, J.-P., Renouard, C., Sauter, J., Scheurer, O., Verbèque, B., Desbourdes, S., Héliès, F., Lehmann, S., Saby, N., Tientcheu Nguenkam, M.-E., Jamagne, M., Laroche, B., Bardy, M., Voltz, M. (2014). La cartographie des sols à moyennes échelles en France métropolitaine. *Etude et Gestion des Sols* 21: 25-36.
- Richer de Forges, A., Arrouays, D., Bardy, M., Bispo, A., Lagacherie, P., Laroche, B., Lemerrier, B., Sauter, J., Voltz, M. (2019). Mapping of soils and land-related environmental attributes in France: analysis of end-users' needs. *Sustainability* 11 (10), 2940.
- Rijsberman, F. (2006). Water scarcity: Fact or fiction? *Agr Water Manage* 80: 5-22.
- Rizzo, D., Therond, O., Lardy, R., Murgue, C., Leenhardt, D. (2019). A rapid, spatially explicit approach to describe cropping systems dynamics at the regional scale. *Agr. Syst.* 173: 491-503.
- Román Dobarco, M., Bourennane, H., Arrouays, D., Saby, N.P.A., Cousin, I., Martin, M.P. (2019). Uncertainty assessment of GlobalSoilMap soil available water capacity products: A French case study. *Geoderma* 344: 14-30
- Saatchi, S., Harris, N., Brown, S., Lefsky, M., Mitchard, E.T., Salas, W., Zutta, B.R., Buermann, W., Lewis, S.L., Hagen, S., Petrova, S., White, L., Silman, M., Morel, A. (2011). Benchmark map of forest carbon stocks in tropical regions across three continents. *P Natl Acad Sci (USA)* 108: 9899-9904.
- Saby, N., Marchant, B., Lark, R., Jolivet, C., Arrouays, D. (2011). Robust geostatistical prediction of trace elements across France. *Geoderma* 162: 303-311.
- Saby, N., Foucaud Lemerrier, B., Arrouays, D., Leménager, S., Louis, B., Millet, F., Paroissien, J.-B., Schellenberger, E., Squidant, H., Swiderski, C., Toutain, B., Walter, C., Bardy, M. (2014). Le programme Base de Données des Analyses de Terre (BDAT) : Bilan de 20 ans de collecte de résultats d'analyses. *Etude et Gestion des Sols* 21: 141-150.
- Sagris, V., Milenov, P., Wojda, P. and Devos, W. (2013) The harmonised data model for assessing land parcel identification systems compliance with requirements of direct aid and agri-environmental schemes of the CAP. *J Environ Manage* 118: 40-48.
- Samalens, J.-C., Guyon, D., Bories, N., Piou, D., Bréda, N., Wigneron, J.-P. (2012). Satellite-based forest health monitoring using coarse resolution: Emphasis on the 2003 and 2011 droughts over France, IEEE International Geoscience and Remote Sensing Symposium, IGARSS'2012, 22-27 July 2012, Munich, Germany.

- Samson, E., Van der Werf, H.M.G, Dupraz, P., Ruas J.-F., Corson M.S. (2012). Estimer les impacts environnementaux des systèmes de production agricole par analyse de cycle de vie avec les données du Réseau d'information comptable agricole (RICA) français. *Cah Agric* 21: 248-57
- Sarron J., Brun F., Casadebaig P., Rollet P., Mestries E., Debaeke P. (2017). *Diagnostic agronomique des évolutions de rendements du tournesol en France*. Doc. GIS GC HP2E, 4p. [https://www.gchp2e.fr/content/download/3710/37652/version/1/file/Reporting+GC+HP2E\\_debaeke\\_def\\_9janv.pdf](https://www.gchp2e.fr/content/download/3710/37652/version/1/file/Reporting+GC+HP2E_debaeke_def_9janv.pdf)
- Sausse, C., Barbottin, A., Jiguet, F., Martin, P. (2015). Do the effects of crops on skylark (*Alauda arvensis*) differ between the field and landscape scales? *PeerJ* 3: e1097
- Schmidt, A., Guichard, L., Reau, R. (2010). Le colza est très dépendant des pesticides dans les rotations courtes sans labour. *Agreste, Synthèses*, 2010/121, 7 p.
- Sebillotte, M. (1974). *Agronomie et agriculture. Essai d'analyse des tâches de l'agronome*. Cah. Orstom, Sér. Biol., 24: 3-25.
- Shabou, M., Mougenot, B., Chabaane, Z.L., Walter, C., Boulet, G., Ben Aissa N., Zribi M. (2015). Soil clay content mapping using a time series of Landsat TM data in semi-arid lands. *Remote Sens* 7: 6059-6078.
- Shelia, V., Hansen, J., Sharda, V., Porter, C., Aggarwal, P., Wilkerson, C.J., Hoogenboom, G., 2019. A multi-scale and multi-model gridded framework for forecasting crop production, risk analysis, and climate change impact studies. *Env Model Softw* 115: 144-154.
- Terrat, S., Horrigue, W., Dequietd, S., Saby, Nicolas P. A., Lelievre, M., Nowak, V., Tripied, J., Regnier, T., Jolivet, C., Arrouays, D., Wincker, P., Cruaud, C., Karimi, B. Bispo, A., Maron, P.-A., Prevost-Boure, N.C., Ranjard, L. (2017). Mapping and predictive variations of soil bacterial richness across France. *Plos One* 10, e0186766
- Terres Inovia (2016). *Bulletin de Santé du Végétal. Midi-Pyrénées. BSV Bilan 2015 tournesol*.
- Therond O. (coord.), Tichit M. (coord.), Tibi A. (coord.), Accatino F., Biju-Duval L., Bockstaller C., Bohan D., Bonaudo T., Boval M., Cahuzac E., Casellas E., Chauvel B., Choler P., Constantin J., Cousin I., Daroussin J., David M., Delacote P., Derocles S., De Sousa L., Domingues Santos J.P., Dross C., Duru M., Eugène M., Fontaine C., Garcia B., Geijzendorffer I., Girardin A., Graux A-I., Jouven M., Langlois B., Le Bas C., Le Bissonnais Y., Lelièvre V., Lifran R., Maigné E., Martin G., Martin R., Martin-Laurent F., Martinet V., McLaughlin O., Meillet A., Mignolet C., Mouchet M., Nozières-Petit M-O., Ostermann O.P., Paracchini M.L., Pellerin S., Peyraud J-L., Petit-Michaut S., Picaud C., Plantureux S., Poméon T., Porcher E., Puech T., Puillet L., Rambonilaza T., Raynal H., Resmond R., Ripoché D., Ruget F., Rulleau B., Rush A., Salles J-M., Sauvant D., Schott C., Tardieu L. (2017). *Volet "écosystèmes agricoles" de l'Évaluation Française des Ecosystèmes et des Services Écosystémiques. Rapport d'étude*, Inra (France), 966 p.
- Therond, O., Sibertin-Blanc, C., Balestrat, M., Gaudou, B., Hong, Y, Louail, T., Nguyen, V.B., Panzoli, D., Sanchez-Perez, J.M., Sauvage, S., Taillandier, P., Vavasseur, M., Mazzega, P. (2014). Integrated modelling of social-ecological systems: The MAELIA high-resolution multi-agent platform to deal with water scarcity problems. In D.P. Ames, N. W.T. Quinn, A. E. Rizzoli (Eds.). *7th Int. Congress on Env. Modelling and Software (iEMSs)*, San Diego, CA, USA, 8 p.
- Tibi A., Therond O. (Eds.), 2018. *Services écosystémiques fournis par les espaces agricoles. Evaluer et caractériser*. Quae, 186 p.
- Torres, R., Snoeij, P., Geudtner, D., Bibby, D., Davidson, M., Attema, E., Potin P., Rommen, B., Flourey N., Brown, M., Navas Taver, I., Deghaye, P., Duesmann, B., Rosich, B., Miranda, N., Bruno, C., L'Abbate, M., Croci, R., Pietropalo, A., Huchler, M., Rostan, F. (2012). GMES Sentinel-1 mission. *Remote Sens Env* 120: 9-24.
- Urruty, N., Tailliez-Lefebvre, D., Huyghe, C. (2016) *Characterisation and assessment of yield robustness in French wheat cropping systems*. Proc 14th ESA Congress, 5-9 September 2016, Edinburgh, Scotland.
- Vaudour, E., Bel, L., Gilliot, J.M., Coquet, Y., Hadjar, D., Cambier, P., Michelin, J., Houot, S. (2013). Potential of SPOT multispectral satellite images for mapping topsoil organic carbon content over peri-urban croplands. *Soil Sci Soc Am J* 77: 2122-2139.
- Vergriette B. *et al.*, 2018. *Évaluation mettant en balance les risques et les bénéfices relatifs d'autres produits phytopharmaceutiques autorisés ou des méthodes non chimiques de prévention ou de lutte pour les usages autorisés en France des produits phytopharmaceutiques comportant des*



néonicotinoïdes - Tome 3 – Rapport d'appui scientifique et technique sur l'impact agricole à la saison n° 2016-SA-0057, 148 p.

- Vidal, J.P., Martin, E., Franchistéguy, L., Baillon, M., Soubeyroux, J.M., 2010. A 50 year high resolution atmospheric reanalysis over France with the Safran system. *Int J Climatol* 30: 1627-1644.
- Villanneau, E., Saby, N., Marchant, B. P., Jolivet, C., Boulonne, L., Caria, G., Barriuso, E., Bispo, A., Briand, O., Arrouays, D. (2011). Which persistent organic pollutants can we map in soil using a large spacing systematic soil monitoring design? A case study in Northern France. *Sci Total Environ* 409: 3719-3731.
- Vinatier, J.-M., Chafchafi, A., Barjeot, L., Toutain, B., Laroche, B., Arrouays, D., Squidant, H. (2013). Websol : une plateforme Internet de diffusion des données pédologiques. *Etude et Gestion des Sols* 20: 7-18.
- Voinov, A., Bousquet, F. (2010). Modelling with stakeholders. *Env Model Softw* 25: 1268–1281.
- Voinov, A., Kolagani, N., McCall, M. K., Glynn, P. D., Kragt, M. E., Ostermann, F. O., Pierce, S.A., Ramu, P. (2016). Modelling with stakeholders – Next generation. *Environ Modell Softw* 77: 196–220.
- Vörösmarty, C.J., Green, P., Salisbury, J., Lammers, R.B. (2000) Global water resources: vulnerability from climate change and population growth. *Science* 289: 284-288.
- Wagner, D., Quere, L. (2005). Bilan de l'enquête 2004 sur la conduite du tournesol. *Oléoscope* 82: 6-8.
- Wagner, W., Blöschl, G., Pampaloni, P., Calvet, J.-C., Bizzarri, B., Wigneron, J.-P., Kerr, Y. (2007). Operational readiness of microwave remote sensing of soil moisture for hydrologic applications, *Nordic Hydrol* 38: 1–20.
- Waldner, F., Lambert, M. J., Li, W., Weiss, M., Demarez, V., Morin, D., Marais-Sicre, C., Hagolle, O., Baret, F., Defourny P. (2015). Land-cover and crop type classification along the season based on biophysical variables retrieved from multi-sensor high-resolution time series. *Remote Sens* 7: 10400-10424.
- Xiao, Y., Mignolet, C., Mari, J.-F., Benoit, M. (2014). Modeling the spatial distribution of crop sequences at a large regional scale using land-cover survey data: A case from France. *Comput Electron Agr* 102: 51-63.
- Xiao, Y., Mignolet, C., Mari, J.-F., Benoit, M. (2015). Characterizing historical (1992-2010) transitions between grassland and cropland in mainland France through mining land-cover survey data. *Journal of Integrative Agriculture* 14 (8), 60345-7.

APPENDIX

**Table 1. Climatic data**

Type of data	Variables	Methods used to collect or generate the data	Spatial scale	Temporal scale	Data accessibility	Main data providers
Historical data	Observed: temperature, precipitation, wind speed, radiation  Calculated: reference evapotranspiration	Automatic weather stations	600 Météo-France stations + 50 INRAE stations + other private and public networks	Daily data (integrated from hourly data) Historical data (long-term series)	Free for research objectives	Météo-France or other providers such as INRAE
		SAFRAN 8 km resolution atmospheric reanalysis over France	8602 grid cells from SAFRAN (8 km × 8 km)	Daily data (from 1958)	Free for research objectives	Météo-France
Future climatic series		Regional climatic models under RCP scenarios	8602 grid cells from SAFRAN (8 km × 8 km)	Daily data available until 2100	Free	DRIAS portal <a href="http://www.drias-climat.fr">www.drias-climat.fr</a>

**Table 2. Soil data**

Type of data	Variables	Methods used to collect or produce the data	Spatial scale	Temporal scale	Data accessibility	Data provider
National and local soil maps & related databases (inventory)	Physico-chemical data	Field prospection Now digital soil mapping	National: 1:1 000 000 – 1:250 000 Local: 1:10 000 – 1:100 000	Once	Free (on request)	INRAE InfoSols
National soil test database (monitoring)	Physico-chemical data	Topsoil sampling (0-30 cm)	>20 M soil analyses from farm fields Agricultural topsoils	Every 5 yr (from the 1990s)	Available at aggregated level	
Soil Quality Measurement Network (monitoring)	Physico-chemical data + contaminants, biological components, etc.	Composite samples (0-50 cm)	Grid of 16 km × 16 km cells: 2200 sites	From 2001 (every 15 yr)	Free (but anonymized)	

**Table 3. Data on weeds, pests and diseases**

<b>Data collection network</b>	<b>Variables</b>	<b>Methods used to collect or produce the data</b>	<b>Spatial scale</b>	<b>Temporal scale</b>	<b>Data accessibility</b>	<b>Data provider</b>
Réseau "Biovigilance Flore"	Weed presence and abundance (incl. field margins) + related crop management data	Field survey (weed-free and sprayed areas)	1000 fields (georeferenced)	Annual from 2002	Free for scientific partners	Ministry of Agriculture
Réseau de surveillance épidémiologique	Injury incidence or severity	Field observations Epiphyt portal	Network of fields	Several observations each year	Free for scientific partners	Ministry of Agriculture

**Table 4. Land-cover data**

Type of data	Variables	Methods used to collect or produce the data	Spatial scale	Temporal scale	Data accessibility for research	Data provider
RPG (French LPIS)	Directly: Sown crops (type, area)  Indirectly: Crop sequences (using algorithms)	Farmer declaration (online)  Spatial and algorithmic processing of annual RPG	Each islet of each farm that receives CAP subsidies: 27 M ha  Ca. 95% of the islet area	Annual From 2006  2006-2014	Anonymized and simplified version* Full data set	Ministry of Agriculture (SSP service)  INRAE (ODR Service unit)
Teruti & Teruti-Lucas	Land use (25-38 classes) and land-cover (81-88 classes)	Sampling and survey then aerial photography (from 2010)	Teruti: 4700 cells of 12 km × 12 km  Teruti-Lucas: one sample every 178 ha (georeferenced)	From 1981 (Teruti)  From 2005 (Teruti-Lucas)	Regional aggregated data freely available*	Ministry of Agriculture (SSP service)
CORINE Land Cover	Land-cover (44 classes)  Elements of agricultural landscape	Remote sensing: Landsat, SPOT, etc.	Every 5 years	From 1985	Free	Agence Européenne pour l'Environnement (EU)
IOTA2	Land-cover (20 classes in 2016)	Remote sensing: Landsat, Sentinel-1 & -2	Annual	From 2016	Free	THEIA

\* Restricted use of individual data can be made possible via a “Secret Committee” agreement and secure remote access.

**Table 5. Crop management data**

Type of data	Variables	Methods used to collect or produce the data	Spatial scale	Temporal scale	Data accessibility for research	Data provider
“Pratiques Culturales”	Cropping practices for field crops (14), grasslands, horticultural crops and vineyards	Farm surveys	1000-3000 fields per crop, representing 90% of sown area	Every 5 years (since 1986 for field crops) + some data for previous 5 years	Restricted use*	Ministry of Agriculture (SSP service)
“Colza” & “Tournesol”	Cropping practices for oilseed and protein crops	Postal surveys	ca. 1000 fields per year (TBC)	Every 2-3 years (from 1996 – sunflower)	Available for research partners	Terres Inovia
ECOPHYTO-DEPHY “Farm network”	Farm structure, crop management, + (decision rules; field landscape; weed, pest and disease statuses)	Farm surveys  AgroSyst (database)	1900 farms	Annual	Available for research partners	INRAE

\* Restricted use of individual data can be made possible via a “Secret Committee” agreement and secure remote access.

**Table 6. Soil and vegetation survey data (remote sensing)**

<b>Type of data</b>	<b>Variables</b>	<b>Methods used to collect or produce the data</b>	<b>Spatial scale</b>	<b>Temporal scale</b>	<b>Data accessibility for research</b>	<b>Data provider</b>
Canopy data	Observed: reflectance (visible, near-infrared, short-wavelength infrared)  Calculated: normalized difference vegetation index (NDVI), leaf area index (LAI), fraction of absorbed photosynthetically active radiation (FAPAR), biomass	Remote sensing:  Landsat SPOT Sentinel MODIS	10-1000 m (depending on the sensor)	16 days  5-6 days  + Historical archives available	Free	THEIA www.theia-land.fr  NASA www.modis.gsfc.nasa.gov/data
Crop water status	Thermal infrared (surface temperature)	MODIS	ca. 250 m	Daily	Free	