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Long-term changes in greenhouse gas emissions from French agriculture and livestock (1852–2014): From traditional agriculture to conventional intensive systems

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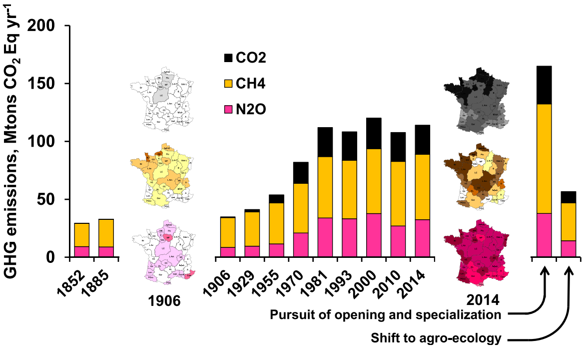
HIGHLIGHTS

- French GHG emissions from agricultural and forest sectors were estimated.
- A long-term trajectory (1852–2014) was reconstructed for N_2O, CH_4, CO_2.
- GHG emissions have grown four-fold since 1852, to 120,000 CO_2 Eq yr^{-1} in the 2000s.
- GHG emissions have only stabilised, in spite of agro-environmental measures.
- Deep changes in the agro-food system would reduce agricultural GHG emissions.

GRAPHICAL ABSTRACT



Keywords:
French agriculture
GHG emissions
Historical reconstruction
Spatial distribution
Scenario analysis

ABSTRACT

France was a traditionally agricultural country until the first half of the 20th century. Today, it is the first European cereal producer, with cereal crops accounting for 40% of the agricultural surface area used, and is also a major country for livestock breeding with 25% of the European cattle livestock. This major socioecological transition, with rapid intensification and specialisation in an open global market, has been accompanied by deep environmental changes. To explore the changes in agricultural GHG emissions over the long term (1852–2014), we analysed the emission factors of N_2O from field experiments covering major land uses, in a gradient of fertilisation and within a range of temperature and rainfall, and used CH_4 emission coefficients for livestock categories, in terms of enteric and manure management, considering the historical changes in animal excretion rates. We also estimated indirect CO_2 emissions, rarely accounted for in agricultural emissions, using coefficients found in the literature for the dominant energy consumption items (fertiliser production, field work and machinery, and feed import). From GHG emissions of ~30,000 ktons CO_2 Eq yr^{-1} in 1852, reaching 54,000 ktons CO_2 Eq yr^{-1} in 1955, emissions more than doubled during the 'Glorious thirties' (1950–1980), and peaked around 120,000 ktons CO_2 Eq yr^{-1} in the early 2000s. For the 2010–2014 period, French agriculture GHG emissions stabilised at ~114,000 ktons CO_2 Eq yr^{-1}, distributed into 49% methane (CH_4), 22% carbon dioxide (CO_2) and 29% nitrous oxide (N_2O). A regional approach through 33 regions in France shows a diversity of agriculture reflecting the hydro-ecoregion distribution and the agricultural specialisation of local areas. Exploring

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contrasting scenarios at the 2040 horizon suggests that only deep changes in the structure of the agro-food system would double the reduction of GHG emissions by the agricultural sector.

1. Introduction

Atmospheric greenhouse gas (GHG) concentrations such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have rapidly increased, especially since the mid-20th century, as shown by ice core and modern data (IPCC, 2008). At the global scale, agricultural activities and land use changes accounted for 24% of the total emissions (IPCC, 2008) (not including indirect emissions such as those linked to fertiliser manufacture). For the European Union (EU-28), agricultural emissions are considered as the second largest GHG contributors after fossil fuel combustion (respectively, 10% vs. 78% of total EU emissions, amounting 4300 million tons CO_2 equivalent, in 2016) (EEA, 2018). For France (out of the 520 million tons CO_2 equivalent yr^{-1}), GHG from agriculture and fossil fuel combustion represented 19% vs. 71%, respectively in 2010, with a decreasing trend since the Kyoto protocol (CITEPA, 2012). Fugitive emissions from fuels represented only 1% of the total GHG emissions, industrial processes accounted for about 3.7% and wastes for 4.8% (CITEPA, 2012). Surprisingly, according to CITEPA, whereas 66% and 87% of CH_4 and N_2O emissions are issued from French agriculture, agriculture is not considered as a source of CO_2, its emissions being included in others sectors (machinery, chemicals, …). Therefore, the role of agriculture in overall GHG emissions, including direct and indirect CO_2 emissions linked to fossil fuel-driven farming practices still present a number of uncertainties (Lemke et al., 2007).

The control factors of agricultural N_2O, CH_4 and CO_2 emissions differ greatly from each other. N_2O fluxes are often reported to be associated with mineral fertiliser applications (Bouwman, 1996; Skiba et al., 1996; Smith et al., 1997; ENA, 2011), particularly on wet non-saturated soils (Clayton et al., 1994; Aguilera et al., 2013), but manure and other organic fertilisers also contribute to N_2O emissions (Aguilera et al., 2013). CH_4 fluxes come essentially from livestock (Moss et al., 2000; Vermorel et al., 2008; Springmann et al., 2018), manure management and enteric fermentation (particularly ruminants), although some soils can be a CH_4 sink through CH_4 oxidation (Boeckx and Van Cleemput, 2001), a capacity that managed agricultural soils have partly lost due to nitrogen fertiliser application, which is unfavourable to methane oxidizing micro-organisms (Ojima et al., 1993; Dobbie and Smith, 1996). In contrast, paddy soils could be net emitters of this gas. While net soil CO_2 emissions result from the balance between humified organic matter input and mineralisation or leaching, CO_2 emissions by agriculture stem more from CO_2 emitted from the fossil fuel use related to fertiliser manufacture, use of machinery for farm work and feed imports (Gingrich et al., 2007; Dyer et al., 2010; Aguilera et al., 2015). How these different control factors combine with each other to determine the variations in time and space of GHG emissions by agricultural systems remains a question that is difficult to answer.

France is currently the world's fourth largest agricultural exporter (www.fao.org/faostat), with a rather diversified mosaic of regional agricultural systems. It therefore constitutes a good case study for analysing the relationships between the structural characteristics of agriculture and its GHG emissions.

Based on the concepts of socio-ecological trajectories (Fischer-Kowalski and Haberl, 2007) and territorial ecology (Barles, 2010; Barles, 2017), the long-term trends of the French agro-food system have been described by Le Noë et al. (2018) in terms of N, P and C fluxes over the period from 1852 to 2014. A gradual intensification and specialisation of regional systems was shown, all characterised by integrated crop and livestock farming until the beginning of the 20th century, toward either specialised cropping systems fueled by synthetic fertilisation or intensive livestock farming highly dependent on external feed imports (Le Noé et al., 2016). Within the country, the Seine watershed is one emblematic example of the former specialised cropping systems, while Bretagne is a region of typical intensive livestock farming systems highly disconnected from croplands. Marescaux et al. (2018) established the GHG budget for the Seine Basin, including the hydrosystem network, the agricultural and non-agricultural sectors. Of the approximately 61,000 ktons CO_2 Eq yr^{-1} emitted from the whole Seine Basin, non-agriculture GHGs were shown to dominate the total emissions (73%), while the agricultural sector amounted to 23% and emissions by rivers reached 4%. The agricultural emissions found for the Seine Basin were 30% higher than those provided by official French GHG emission inventories.

The first aim of this paper is to establish a spatially distributed long-term budget of GHG emissions by the French agricultural sector. A major issue behind this effort is to identify the effect of the structural changes from mixed crop and livestock farming systems to specialised systems on the GHG emissions account. Indeed, the shift of agricultural and livestock management practices which occurred with mechanisation and intensification are expected to cause increased GHG emissions. Moreover, specific emission rates of CO_2, CH_4, N_2O are expected to depend either on crop or livestock typologies. Another objective is to determine the levers for future mitigation of N_2O, CH_4 and CO_2 emissions by agricultural practices. In this line, we explored two contrasting scenarios recently developed by Billen et al. (2018): (i) continuing the current trends of specialisation into either cropping systems based on chemically synthesised inputs or intensive livestock farming highly dependent on feed import; and (ii) shifting to organic farming and reconnection of crop and livestock farming, while reducing the animal proteins in human diets by half. These two prospective scenarios of French agriculture are tested in order to evaluate to which extent less intensive agriculture and livestock breeding can allow a reduction of GHG emissions.

2. Material and methods

2.1. Major physiographic and agricultural characteristics of France

France is a heterogeneous country with a mountainous region in the South-East and low relief in the West (Bretagne) as well as large sedimentary plains in the lower part of the Seine, Loire and Garonne rivers flowing to the Atlantic façade. From north to south, there is a climate gradient: temperate, oceanic, temperate warm, and Mediterranean climatic zones (Fig. 1a). These regions are dominated by field crops in the South-West and North-West parts of the country, with Bretagne dominated by intensive livestock farming (Fig. 1b). The rest of France (in the South-East) is either characterised by large vineyard domains in the areas bordering the Mediterranean Sea or in the Rhone alluvial corridor, and by varied mixed crop and livestock in the mountainous regions (the Alps, the Jura and the Massif Central). With 33 regions defined by aggregation of the 94 metropolitan départements (Le Noë et al., 2017), we defined three supra-regions, with a similar surface area, with homogenous agricultural patterns and climate for each: (i) the Seine Basin, due to its intensive cereal cropping agriculture and temperate climate, (ii) the oceanic-temperate Great West, including the Bretagne region and the lower Loire basin with intensive livestock, and the Great South-West covering the Garonne basin, with a temperate warm climate, particularly conducive to growing maize for feed purposes (Fig. 1c).

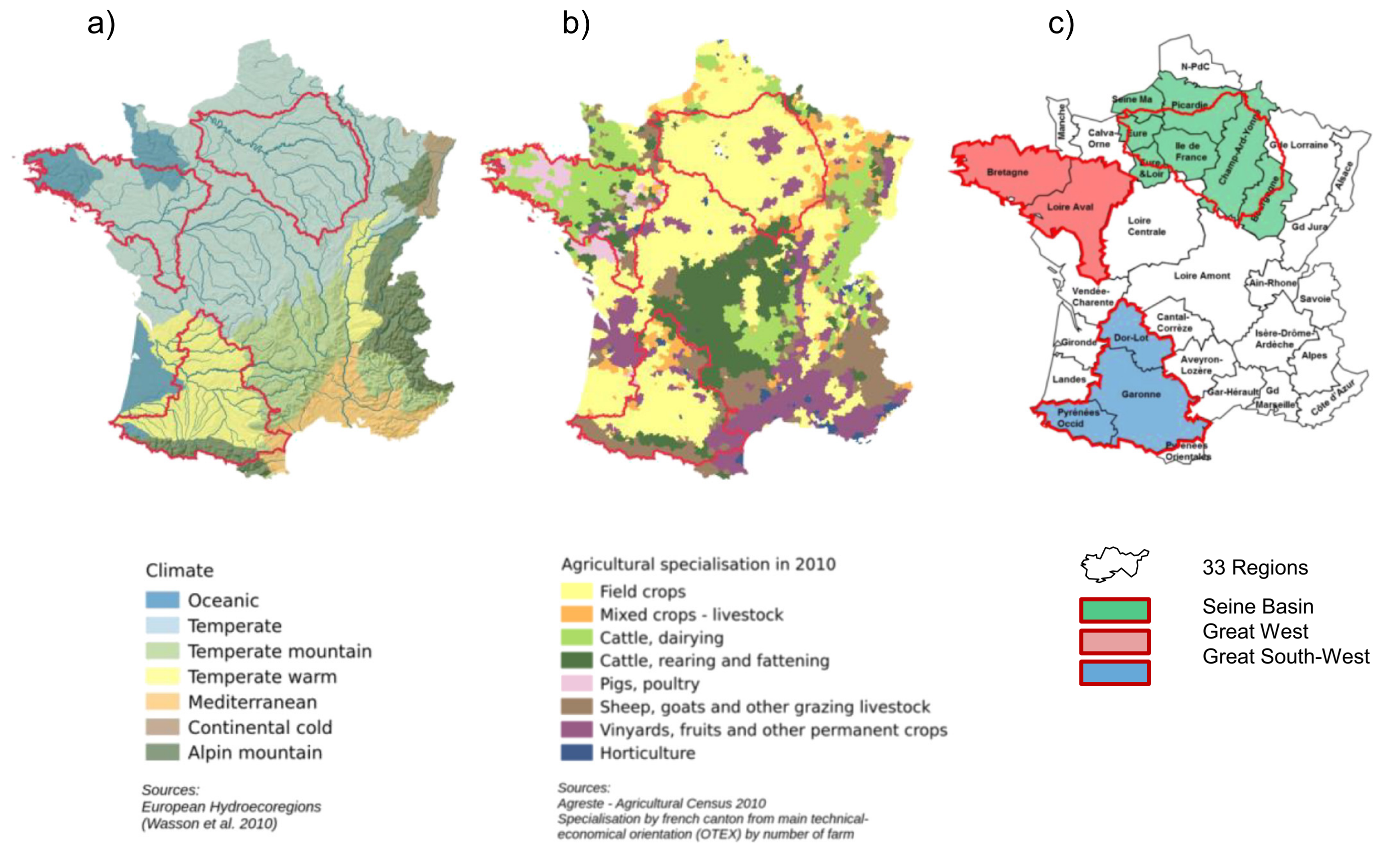

Fig. 1. General characteristics for France of a. climate from hydroecoregion; b. agricultural patterns; c. homogenous agricultural regions (33) and perimeter of three supra-regions chosen for their identical surface area and their trend for agricultural specialisation.

2.2. Reconstruction of past land use and agricultural system

2.2.1. The GRAFS approach for characterising the agricultural structure over the long term

The GRAFS approach (Generalized Representation of Agro-Food System), firstly developed and applied on a global scale (Billen et al., 2013, 2014; Lassaletta et al., 2014a) to local scales (Garnier et al., 2016) for nitrogen (N) circulation, was enlarged to phosphorus (P) (Garnier et al., 2015) and now to N, P and carbon (C), (Le Noë et al., 2017). Briefly, the GRAFS approach describes the agro-food system of a given geographical area by considering four main compartments exchanging nutrient flows: cropland, grassland, livestock system and local population. The potential losses to the environment associated with these exchanges have been estimated for hydrosystems (Garnier et al., 2015, 2016, 2018), but not yet for losses to the atmosphere. This functional representation links arable land productivity, semi-natural or managed grassland that contributes to livestock feeding, and finally, human food requirements. The agro-food system is driven by (i) nutrient inputs to the soil (synthetic and/or organic fertilisation, atmospheric deposition [hereafter referred to as exogenous fertilisation] as well as symbiotic fixation), (ii), the size of the livestock and its feed requirement and (iii) the size of the human population and its dietary preferences, including feed and food imports/exports. The GRAFS approach does not take into account forested areas.

Based on the long-term agricultural statistics available at the scale of the 94 French administrative "département" units for metropolitan France (equivalent to the European Union NUTS3 statistical division) and additional data gathering (e.g. the forested areas below), the GRAFS approach was documented for 22 dates from 1852 to 2014, and for the 33 French regions (Le Noë et al., 2017, 2018), (Fig. 1).

2.2.2. Past evolution of forested areas

The surface forest and wooded areas were documented by "département" for the years 1929 (Ministère Agriculture – Enquête Agricole), 1946, 1950, 1955, 1960 and 1965 (Ministère Agriculture – SAA). All years were available from 1970 to 1988 based on data provided by Agreste-SSP. The recent years from 1989 to 2014 were retrieved from the AGRESTE database on agricultural statistics (https://stats.agriculture.gouv.fr/disar-web/). For France, whereas the total surface areas amounted to $10.67 \cdot 10^6$ ha in 1929, examining the chronicle by Cinotti (1996) for the 19th century showed values around $9.3 \cdot 10^6$ ha in 1850 (compared to the $10.67 \cdot 10^6$ ha in 1929) and a linear trend for the intermediate dates, 1885 and 1906. The same changes were applied to the 33 regions, for the dates before 1929.

2.3. Reconstruction of greenhouse gas emissions

As a whole, the GHG budget of the agriculture sector can be estimated as the result of N_2O emissions from cropped soils, grassland and forest, CH_4 released from livestock production (enteric fermentation and manure management) and CO_2 emitted from fossil fuel directly used by farming practices as well as indirectly for manufacture and transport of agricultural inputs. Due to their specific origin, each of these GHG emissions required an adapted methodology. Agricultural soil C sequestration has been estimated elsewhere and will be compared to GHG emissions (Le Noë et al., 2019).

2.3.1. Reconstruction of N_2O emissions

To infer N_2O emissions back to 1852 at the scale of the 33 regions of France, on the basis of the recent knowledge gained from field measurements, we first established an empirical relationship linking yearly N_2O emissions to mineral and organic fertilisation, temperature and rainfall, and then assumed that this relationship could be extrapolated to past situations within the timeframe of this study (e.g. Bouwman et al., 2013).

For N_2O emissions, a literature review from Garnier et al. (2009) and Cayuela et al. (2017) was completed for a total of 208 yearly cropland N_2O emissions values and their associated explicative variables, namely N fertiliser (organic and mineral) inputs, annual mean temperature and rainfall. A similar set of data was gathered for 138 cases of grasslands. For forests, we found 48 cases for N_2O emissions that were only associated with temperature and rainfall data, since they had not been fertilised. Additional early field measurements from the Seine watersheds were also included in this analysis (Benoit et al., 2015a, 2015b). The complete data set is presented in the supplementary material (SM1).

We searched the best fit parameters for the following relationship:

$$N_2O_{em} = \left(a + b\, {N_{inp}}^{d}\right) * (Rain/Rain_{ref})^{c} * {Q_{10}}^{T/10}$$

where N_2O emissions (N_2O_{em}) and N inputs (N_{inp}) are in kg N_2O-N ha^{-1} yr^{-1}, rainfall (Rain) in mm yr^{-1} and temperature (T) in °C (Table 1), and a, b, c, $Rain_{ref}$, d and Q_{10} are parameters to be calibrated within a range of realistic values.

This relationship assumes a power function for the relationship with N inputs and rainfall, and a classical Q10 exponential relationship with temperature.

Since most grassland was fertilised, no significant difference was found between cropland and grassland so that the two data series were merged. Regarding forests, Ninputs are restricted to atmospheric deposition and a specific relationship was established (Table 1).

The six parameter values (a, b, c, d, $Rain_{ref}$ and Q10) were determined by a systematic optimisation procedure searching the combination of parameter values providing the best fit of the calculated emissions to the observed N_2O emission values. The resulting relationship fits the data with an acceptable % bias (ratio of mean calculated values to mean observed values) and Normalised RMSE (root mean square error normalised against the range of observed values) (Table 1). Further details on the procedure are provided in Supplementary material (SM2).

Table 1
a. Summary of the data gathered for establishing relationships between N_2O emissions and its controlling factors, n = 394, number of data. Relationships, and associated parameter values: b. for cropland and grassland and c. for forest. NRMSE and bias are calculated for evaluation of the fitted relationships.

a.

N = 394	Nb of values	N inputs, kgN ha^{-1} yr^{-1}	Rainfall, mm yr^{-1}	Temperature, °C	N_2O emission, kgN-N_2O ha^{-1} yr^{-1}
Cropland	208	0–450	327–1250	2.75–18.5	0.01–11.0
Grassland	138	0–753	400–1837	1.00–16.0	−0.50–18.9
Forest	48	0	607–1239	3.60–10.1	0.17–4.9

b.

$N_2O_{em} = (a + b\, {N_{inp}}^{d}) * (Rain / Rain_{ref})^{c} * {Q_{10}}^{T/10}$

	Units	Value	± step
a	kgN/ha/yr	0.15	0.05
b	dimless	0.016	0.001
c	dimless	1.2	0.05
d	dimless	1.0	0.1
$Rain_{ref}$	mm yr^{-1}	1000	100
Q_{10}	dimless	1.2	0.2
nRMSE = 14%			
bias = 5%			

c.

$N_2O_{em} = a * (Rain / Rain_{ref})^{c} * {Q_{10}}^{T/10}$

	Units	Value	± step
a	kgN/ha/yr	1.9	0.05
c	dimless	1.2	0.1
$Rain_{ref}$	mm yr^{-1}	1400	100
Q_{10}	dimless	1.2	0.2
nRMSE = 23%			
bias = 10%			

These relationships were applied to cropland and grassland on one hand and to forest on the other hand for each region and 22 dates from 1852 to 2014. Temperature and rainfall were reconstructed from EOPS data for the 1950–2017 period (Version 17, 0.25 degrees resolution (https://www.ecad.eu/download/ensembles/download.php) and spatially averaged by French "département" (NUTS-3 equivalent). For the period prior to 1950, temperature and rainfall data were downloaded for 28 towns spread over the country, back to the dates available in the past, between 1850 and 2017 (http://meteo-climat-bzh.dyndns.org/mete100-1783-2018-3-tn-1-0-0.php). To avoid any discrepancy between the two series, the anomaly for each town was calculated compared to the mean over the long-term period and then added to the mean calculated for the 1950–2017 period. The values prior to 1950 for the towns were then assigned to their respective regions. The same procedure was applied for both temperature and rainfall. The average differences between the two data series for the 1950–2017 period for all 33 regions is close to zero (i.e., no systematic bias) with a standard deviation of 15%, for temperature and rainfall.

2.3.2. Reconstruction of CH_4 emissions

CH_4 emissions were estimated based on livestock numbers and specific emission factors for each animal and age class category, corrected for past variations in excretion rates.

Current CH_4 emission factors (kg-CH_4 $head^{-1}$ $year^{-1}$) from enteric fermentation and manure storage and management were taken from Garnier et al. (2013, see Table 1SM) compiled principally from Vermorel et al. (2008), IPCC (1997) and Zhou et al. (2007). An emission factor for humans was also taken into account, following Crutzen et al. (1986).

These CH_4 emissions concerned five animal sub-categories for cattle, three for sheep, three for pig, five for poultry, while goat, horse and rabbit represented one category each. Knowing the number of heads per category and the associated manure produced, the total amount of CH_4 emitted by livestock was calculated using the corresponding specific emission factors.

Livestock numbers per category were taken directly from agricultural statistics (Agreste, or Gallica (https://gallica.bnf.fr) when these numbers were not available from Agreste). However, the evolution of animal size and physiology changed over the period studied (Chatzimpiros, 2011) and this must be taken into account. Historical variations of excretion rates of the major livestock categories were established by Le Noë et al. (2018, SM1 & SM2) (Table 2). The correction factors found during the period for the animal categories reported in Table 2 were also used for their corresponding sub-categories. For poultry and rabbit, no change was considered over time.

Table 2
Empirical relationship for calculating excretion rates (y, in kgN $head^{-1}$ yr^{-1}) of cattle, sheep, pig and horses as a function of time (t, in year) over the period 1850–2014, and corresponding values of the parameters b, a, a′, tmax and dt, calibrated against historical and current animal excretion data.
(From Le Noë et al., 2018.)

	b	a	a′	t_{max}	dt
	kgN $head^{-1}$ yr^{-1}	kgN $head^{-1}$ yr^{-1}	yr	yr	yr
Cattle	45	0.05	65	2010	40
Sheep	4	0.02	9	2020	45
Pig	56	0.034	–	–	–
Horse	480	0.3	–	–	–

General formula: $y = b + a\,(t - 1850) + a'\exp\left[-(t - t_{max})^2 / dt^2\right]$.

2.3.3. Reconstruction of CO_2 emissions

Current CO_2 emissions by direct or indirect fossil fuel combustion by the agricultural sector were calculated using the official French CLIMAGRI approach (Doublet, 2011), based on CO_2 emission factors calculated for mechanised field work and livestock activities, as well as for synthetic fertiliser manufacture. The coefficients used are gathered in Table 3.

The coefficients related to mechanisation (fossil fuel combustion for machinery, field work in cropland and grasslands, and livestock management and feed to livestock) were applied pro-rata to the usable agricultural area or the total livestock units for each region, and extrapolated to the past taking into account the degree of mechanisation of each region. The proxy for establishing this degree of mechanisation was based on the observed evolution of the numbers of horses between 1906 (zero mechanisation) and 1980 (100% mechanisation) (Fig. 2).

2.4. Exploring scenarios

The two contrasting scenarios recently developed by Billen et al. (2018) are explored herein in terms of GHG emissions for their divergent assumptions: one continuing the trends of **O**pening to distant markets and **S**pecialisation into either cropping systems based on synthesised external inputs or intensive livestock farming (O/S), the other with an agricultural system shifting to **A**utonomy through organic farming, crop and livestock **R**econnection and a **D**emitarian diet (A/R/D). The O/S scenario reflects a main stream vision mainly driven by the desire for economic growth, very present in the official discourse, which is accompanied by the strengthening of territorial specialisation in a globalised economy, the continuation of agricultural intensification and the concentration of the population in large cities. On the contrary, the A/R/D scenario assumes a radical rupture toward agro-ecology (Billen et al., 2018) and organic farming, searching for the autonomy of farmers with respect to agricultural inputs such as N fertilisers and animal feed, and reduction of the share of animal protein in the human diet as recommended by, for example, WHO for health reasons and Springmann et al. (2018) for environmental reasons, all trends already detectable although far from being fully underway. We here assumed reducing the animal proteins in human diets by half following the so-called demitarian diet (see the Barsac declaration, in 2009; https://en.wikipedia.org/wiki/Demitarian). Both scenarios were tested for the 2040 horizon and we therefore considered an increase of 1.5 °C for both scenarios in addition to the 1.5 °C already observed since the end of the 19th century. We kept the rainfall as it is at present because no general trend has been observed, in spite of yearly oscillations over the studied period. These projections are well in the ranges of those reported in Jouzel et al. (2014) for France for 2050, with four different models. Changes in rainfall might be more visible at the seasonal scale, not investigated here, with wetter winters and drier summers, and increased occurrence of extreme weather events in all seasons. Regarding fertilisation, both the O/S and A/R/D scenarios follow current environmental regulations, external synthetic fertilisers will be used according to a yield objective for the former, while the latter banish the use of mineral fertilisers (and pesticides) replaced by biological nitrogen fixation and possibly by on-farm and recirculated external organic inputs. In both scenarios, the livestock species structure was kept identical to the current one (2004–2014) for the regions that already had livestock.

Table 3

Coefficient applied for the calculations of CO_2 emissions according to major emitter sectors. N fertilisers and P fertilisers concern the production of fertilisers actually used, feed to livestock is the imported feed, machinery corresponds to the manufacture of agricultural equipment, energy for cropland, grassland and livestock, the fuel or electricity necessary for fieldwork and for livestock breeding.
(From Doublet, 2011.)

Major sectors emitting CO_2	Units	Coefficients
Fertilisers N	tonC-CO_2/tonN	1.12
Fertilisers P	tonC-CO_2/tonP	0.46
Feed to livestock	tonC-CO_2/tonN imported	1.339
Machinery	tonC-CO_2/ha/yr	0.026
Energy for cropland	tonC-CO_2/ha UAA/yr	0.077
Energy for grassland	tonC-CO_2/ha UAA/yr	0.055
Energy for livestock	tonC-CO_2/LU/yr	0.056

UAA: utilised agricultural area; LU: livestock unit.

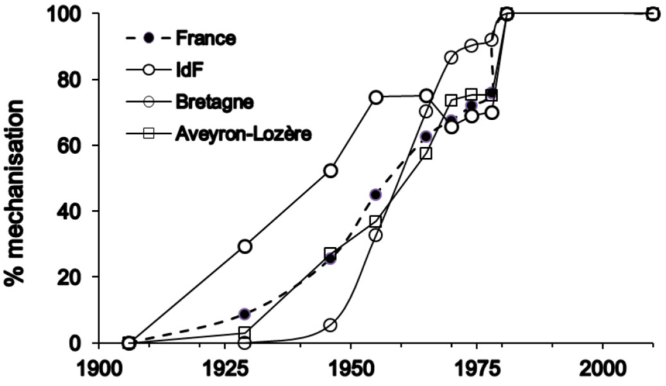

Fig. 2. Evolution of the coefficient of mechanisation from 1906 (zero mechanisation) to 1980 (100% mechanisation) as calculated from the decreasing number of horses for each of the 33 regions. The coefficient is given here for France and three contrasted regions. Agriculture modernisation appeared earlier in Ile-de-France.

2.5. Uncertainty analysis

The GHG emission values calculated as described above result from complex calculations based on basic statistical data (fertilisation rates, livestock number, etc.) and a number of parameters (coefficient of statistical relationships, emission factors, etc.), both subject to a certain level of uncertainty. In order to assess how these uncertainties propagate to the final emission estimates, a bootstrap procedure was carried out, as developed by Le Noë et al. (2018), under Microsoft Excel and associated VBA macros. Shortly, after having stated the confidence interval of all primary data and parameters (typically 10–20% uncertainty was assumed), thousand independent estimations of the GHG emissions were computed with a random draw of each of these data and parameters according to a Monte Carlo sampling within a Gaussian distribution inside the confidence interval. The uncertainty on the final GHG emissions was calculated as the standard error of the mean of these thousand replicates.

3. Results

3.1. Long-term trends of the control variables of GHG emissions

3.1.1. Temperature

A 1.5 °C increase of mean annual temperature was observed between the mid-19th century and the last decade for all of France, mainly from 1980 when the average temperature exceeded 10 °C (Fig. 3). The same trend was observed for the three selected regions, the Great South-West being closer to the overall average and the Great West showing the largest difference (-0.3 °C) (Fig. 3). The coldest and warmest regions are, respectively, Alpes (7 °C) and Grand Marseille (13 °C) in the South-East of France. Regionally, whereas the temperature increase was >1.7 °C in the East, South and South-West of France, with, respectively, a continental and Mediterranean climate, other mountainous regions (Jura, Savoie, Pyrénées) and oceanic temperate (Bretagne), showed an increase of 1.1 °C.

3.1.2. Rainfall

Average rainfall over the period studied (1852–2014) was 805 mm yr^{-1} for the whole of France, more or less 100 mm yr^{-1} for

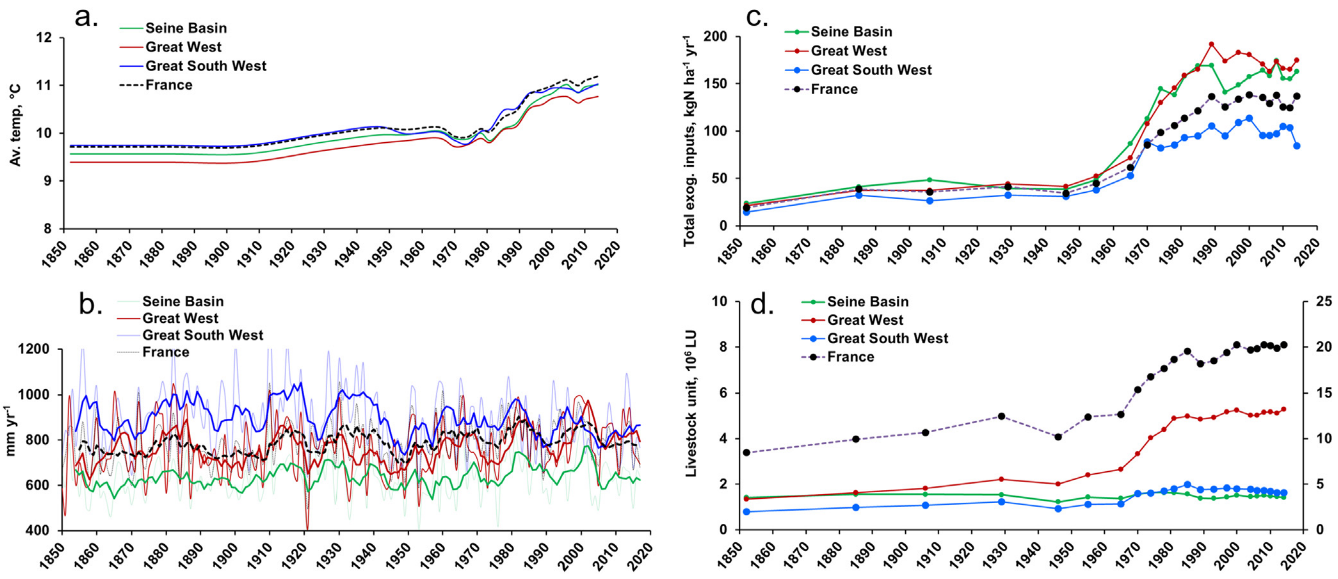

Fig. 3. Long-term evolution (1850–2014) for France and the three supra-regions selected in the annual average of a. temperature; b. rainfall. Long-term evolution of major indicators of agriculture in France and the three supra-regions selected for the 22 dates analysed; c. total exogenous N inputs; d. livestock size in terms of livestock units (LU), right axis for France LU.

the Great South-West (935 mm yr^{-1}) and Seine basin (703 mm yr^{-1}), respectively, whereas rainfall in the Great West averaged 746 mm yr^{-1} (Fig. 3). The wettest regions (>1000 mm yr^{-1}) were Savoie, Pyrénées Occidentales and Landes and the driest was Ile-de-France (~600 mm yr^{-1}). No clear trend was observed over the long term, but wet and dry years alternated (Fig. 3).

3.1.3. Exogenous fertiliser

This accounts for total N inputs (synthetic, manure and deposition), excluding biological nitrogen fixation. From the 1850s until 1965, fertilisation increased from 20 to 60 kgN ha^{-1} yr^{-1}, and more in the early 1970s when half of the regions received 100 kgN ha^{-1} yr^{-1}. The inputs plateaued from the late 1980s at about 135 kgN ha^{-1} yr^{-1} at the national scale. The Northern part of France firstly increased its fertilisation, especially for the fertile soil of Ile-de-France and Nord-Pas-de-Calais, with values exceeding 150 kgN ha^{-1} yr^{-1} in the 1980s (Fig. 3). There were few regions where fertilisation remained below 100 kgN ha^{-1} yr^{-1} until now (Savoie, Alpes, Côte d'Azur in South-East France, and Garonne, Pyrénées Orientales in the South-West), mostly mountainous areas. In these regions, mineral fertilisation was less than half the total exogenous N inputs. Before 1965, fertilisation was essentially based on manure.

The same trend was found for the three selected regions, the Seine Basin and Great West fertiliser trajectory being above the average, and the Great South-West below (Fig. 3).

3.1.4. Livestock

Livestock density, expressed in livestock units (LU, i.e. equivalent to an animal excreting 85 kg N yr^{-1}) per ha of agricultural surface, increased slowly in all French regions until the mid-20th century. The increase was more pronounced in the 1950–1980 period, except in those regions specialising in stockless crop farming, such as the Seine Basin (Figs. 3, 4). The Great West, specialising in intensive livestock farming, dependent on feed import, showed the highest increase in livestock density (Le Noë et al., 2018). Differences among regions stabilised after the 1990s (Fig. 4).

3.2. Agricultural features

We chose three dates (1906 as a reference for traditional agriculture in France, 1970 characterising the beginning of modernisation and 2014 for evidencing the results of specialisation). These agricultural features are mapped for all 33 regions.

3.2.1. Cereal crop production and livestock density

The specificity of the French regions was already in place in the early 20th century with the northern half of France producing 10–-25 kgN ha^{-1} yr^{-1} embedded in the harvested grain, similar to two other regions in the South (West: Garonne; East: Grand Marseille). Ile-de-France already distinguished itself as the most productive (Fig. 4a). At this time in 1906, the regions with the highest livestock density were generally associated with those with high cereal production, showing the importance of the crop–livestock connection at that time. Specialisation had already appeared in 1970, with an intensification of cereal production in the Seine Basin and a rise in livestock breeding most particularly in Bretagne and Loire Amont. In 2014, the decoupling between crop production and livestock is striking: one map is almost the opposite of the other (Fig. 4b).

3.2.2. Percentage of permanent grassland and forest

Except in the Seine Basin, grassland was present over the entire country in 1906, occupying up to 60–80% of the total agricultural area in the South-Eastern quadrant of France (Fig. 4c), and in some other regions with (Manche) or without (Pyrénées) high livestock density. In the 1970s, this trend was accentuated, whereas in 2014 grassland was regressing everywhere. The overall forest area increased in proportion throughout the 20th century but more in the South-East of France and the South-Western border of the Massif Central (Fig. 4d).

3.3. Distribution of GHG emissions over the long term

3.3.1. N_2O

By construction, N_2O emissions by cropland, grassland and forested areas (the sum of their surface areas forms the rural area, in km^2) reflect the long-term spatial and temporal variations in temperature, rainfall and fertilisation of agricultural land. The highest value (75–125 kg N-N_2O km^{-2} yr^{-1}) found for Ile-de-France in 1906 was typically related to its early use of mineral fertilisers (Fig. 5a), whereas the values for Côte d'Azur would be more a combination of fertilisation and temperature/rainfall. The same can be said for the North of France region on the one hand and the South and Center of France regions on the other hand, for the 50- to 75-kg N-N_2O km^{-2} yr^{-1} category. For a majority of regions, N_2O emissions showed a great increase in the 1970s, recently

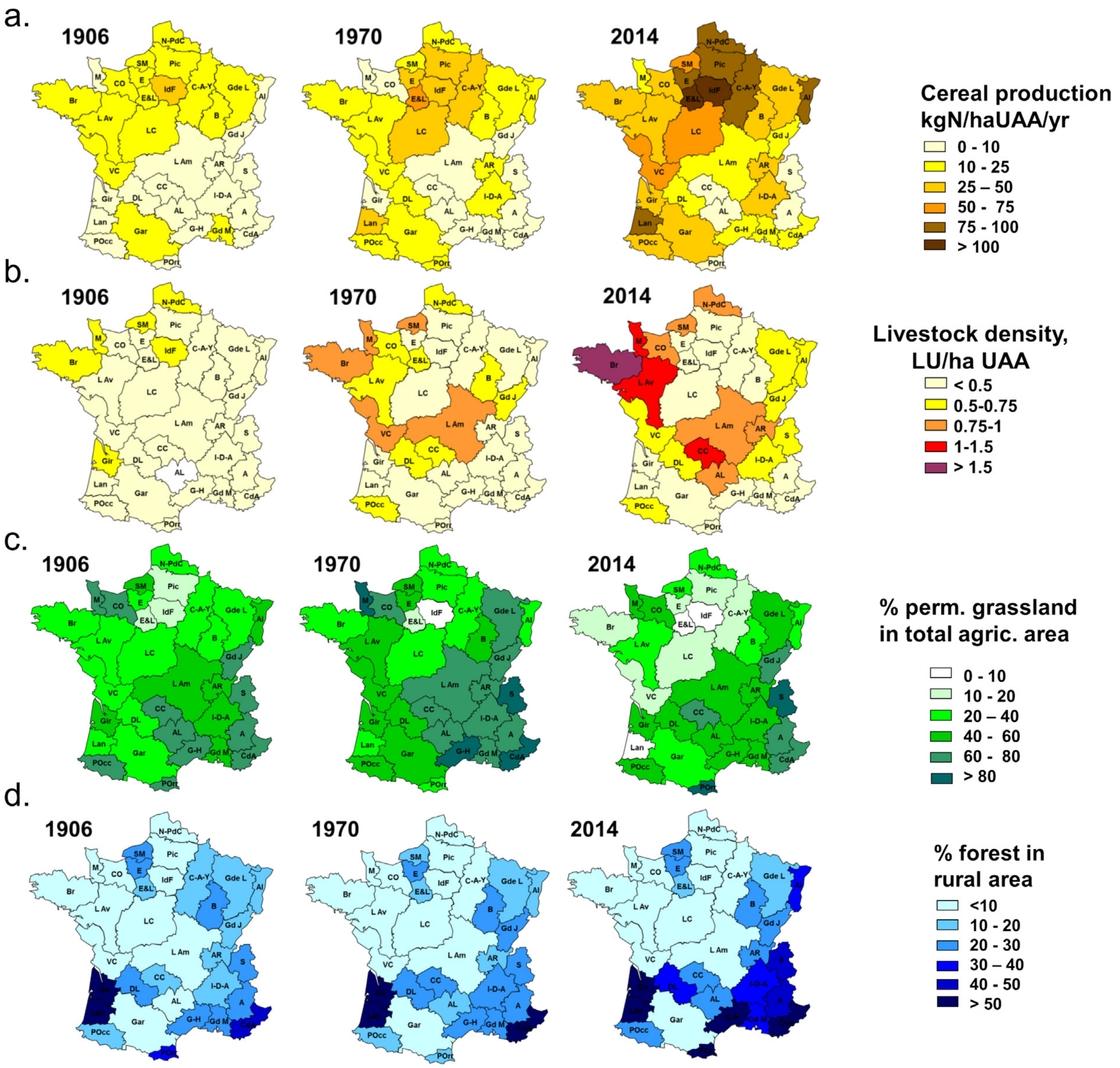

Fig. 4. Maps of regional distributions in France for three dates (1906, 1970, 2014) representative of major time periods: a. cereal production; b. livestock density; c. percentage of permanent grassland in total agricultural area; d. percentage of forest in rural area (i.e. cropland + grassland + forest). UAA, utilised agriculture area. A: Alpes; Al: Alsace; AL: Aveyron-Lozère; AR: Ain-Rhône; B: Bourgogne; Br: Bretagne; C-A-Y: Champagne-Ardennes-Yonne; CC: Cantal-Corrèze; CdA: Côte d'Azur; CO: Calvados-Orne; DL: Dordogne-Lot; E: Eure; E&L: Eure-et-Loire; Gar: Garonne; Gd J: Grand Jura; Gd M: Grand Marseille; Gde L: Grande Lorraine; G-H: Gard-Hérault; Gir: Gironde; I-D-A: Isère-Drôme-Ardèche; IdF: Ile de France; L Am: Loire Amont; L Av: Loire Aval; Lan: Landes; LC: Loire Centrale; M: Manche; N-PdC: Nord Pas-de-Calais; Pic: Picardie; Pocc: Pyrénées Occidentales; POr: Pyrénées Orientales; S: Savoie; VC: Vendée-Charentes.

reaching or exceeding 250 kg N-N_2O km^{-2} yr^{-1} in 2014, i.e. doubling over the 20th century.

3.3.2. CH_4

The distribution of C-CH_4 emissions in time and space, even more than the livestock density map, clearly reflects the patterns of intensification and specialisation that persisted for the whole period studied (Fig. 5b). In brief, a large ring of high emissions was emerging in 1906 around the Seine Basin and was accentuated in 1970 and even more in 2014, when livestock density was reduced giving way to intensive cropping. From emission values generally lower than 2000 kgC-CH_4 km^{-2} yr^{-1} in 1906, they increased to above 6000 kgC-CH_4 km^{-2-} yr^{-1} in the regions specialising in intensive livestock farming.

3.3.3. CO_2

The highest emissions of CO_2 in 1906 are directly linked to the small amount of fossil fuels used for mineral fertilisers because no mechanisation and no feed import were considered (Fig. 5c). The 1970 map resulted from the post Second World War (WWII) increase of all items taken into account in the calculation (fertiliser production, fossil fuels used for field work, machinery and feed import) the proportion of which was modulated from one region to another according to their rate of modernisation and specialisation. For example, in 1970 feed import concerned essentially Bretagne, Nord-Pas-de-Calais and Loire Centrale, also affected by high fertilisation and mechanisation. In 2014 the highest emissions in Bretagne typically related to increasing feed imports from South America (Billen et al., 2011; Le Noé et al., 2016).

3.4. Estimating GHGs under contrasting scenarios

For the O/S scenarios all GHG emissions would increase considerably (Fig. 6). The approximately 20% increase of N_2O emissions for the entire French territory would not be related to nitrogen synthetic fertilisers,

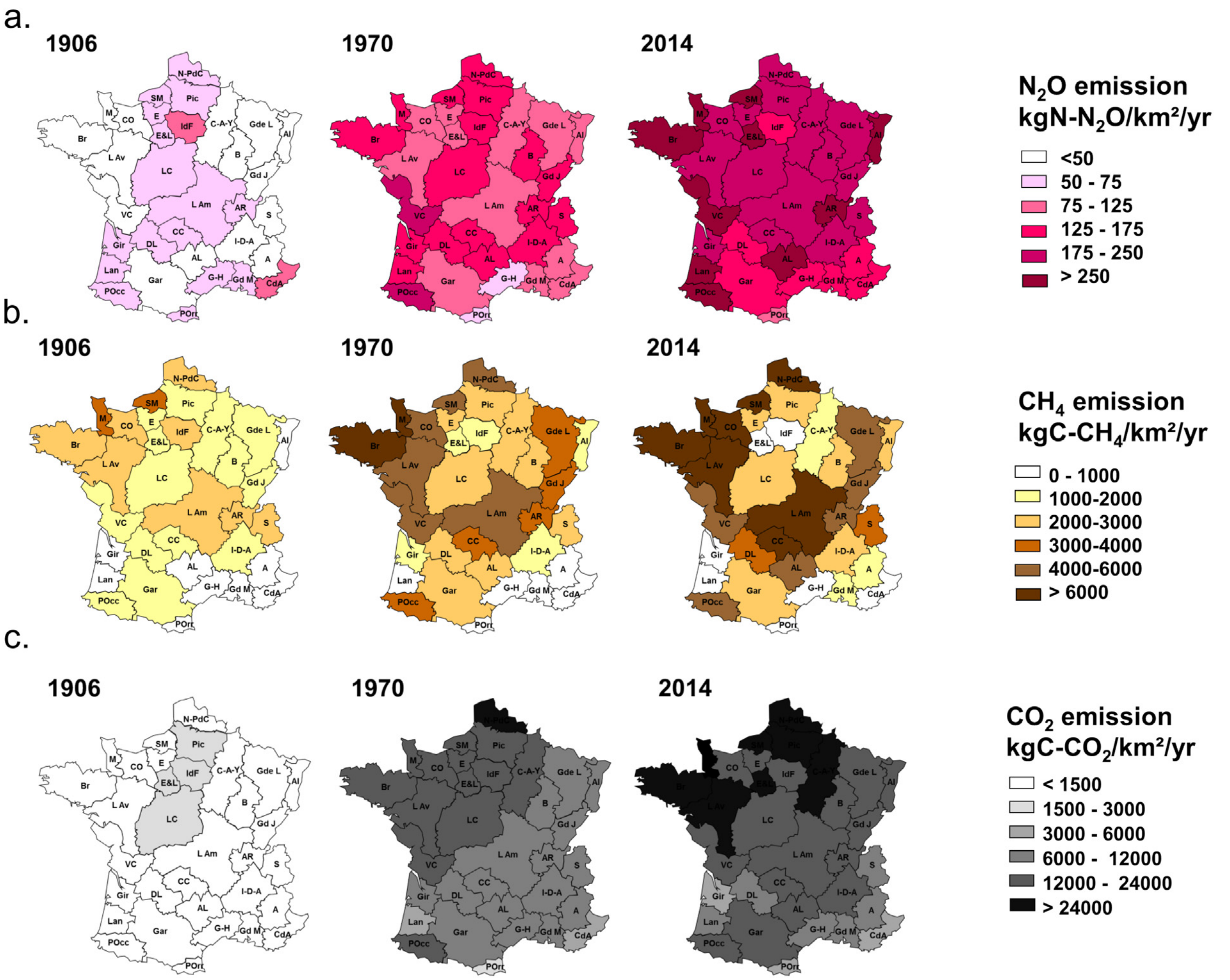

Fig. 5. Maps of regional distributions in France for three dates (1906, 1970, 2014) representative of major time periods of GHG emissions per km^2 of rural areas (cropland + grassland + forest) and per year: a. N_2O; b. CH_4; c. CO_2. See legend of Fig. 4 for the names of the regions.

which are not increasing significantly owing to environmental regulations, but rather to manure application in livestock farming regions (Billen et al., 2018). The Seine Basin, as well as other regions such as Alsace and Landes, emptied of their livestock under extreme specialisation into stockless crop farming, would emit only very low CH_4 while the rest of France would show as high emissions as the most current emitting regions (>6000 kgC-CH_4 km^{-2} yr^{-1}) (Fig. 6) because they have reached the maximum authorised livestock density (European Nitrate Directive (91/676/CEE), i.e. 2 LU ha^{-1} of agricultural area). CO_2 emissions would concomitantly increase mostly in breeding areas, due to feed imports, necessary after a loss in grassland and increased livestock density, in addition to C-CO_2 from fuel consumption and fertiliser production.

Under the A/R/D scenario, the reduction of GHG emissions would allow a “return” to the emissions before the heavy industrialisation of the 1970s and even 1955 (see Fig. 7) depending on the regions. The A/R/D scenario showed that (i) autonomy with respect to synthetic mineral fertilisers would significantly reduce N_2O emissions, (ii) the decrease in animal loading to meet local feed autonomy would lower CH_4 emissions and (iii) CO_2 emissions would be also considerably lowered due to lack of both synthetic fertiliser use and feed imports (Fig. 6). This would allow France to achieve GHG emission targets committed to within the COP-21.

The results of these two scenarios for the three GHGs were put into perspective with their respective historical trajectory for the whole nation and for the three regions selected to distinguish the origin of emissions. We thus corroborate our choice of the three dates illustrating three periods: 1906 for its traditional agriculture (until 1955), the 1970s for this period's transitional status, and 2014, typical of intensive production and specialisation since the 1980s.

Whatever the date, croplands were the major N_2O emitters compared to forests and grasslands, especially in the Seine Basin and the Great West (Fig. 7), whereas the O/S scenario would not significantly change the pattern and the level of N_2O emissions for these two emblematic specialised regions. The Great South-West, assumed to develop high livestock density, hence imported feed, while optimising its crop production in this scenario, would not only increase N_2O but all three GHG emissions. Concerning CH_4, enteric fermentation dominated CH_4 emission, which overall accounted for 70% of the total, and manure (30%) increased in proportion in the O/S scenario for the Great West, traditionally livestock oriented, but also in the Great South-West, as shown by the fourfold increased CH_4 emissions. For CO_2, concomitantly and consequently, imported feed was the dominant emitter sector in the Great West, which would remain so in the O/S scenario, differently from the Great South-West which, as for cropping, revealed its potential for more livestock, and imported feed, with more CO_2 emissions (Fig. 7).

3.5. Comparative agricultural GHG emissions in CO_2 equivalent

The GHG emission can be calculated in a single unit (CO_2 equivalent, CO_2 Eq) by multiplying the global warming potential (GWP) of the different sources with their respective emissions. CO_2 taken as a reference has a GWP of 1, whereas N_2O and CH_4 GWPs are,

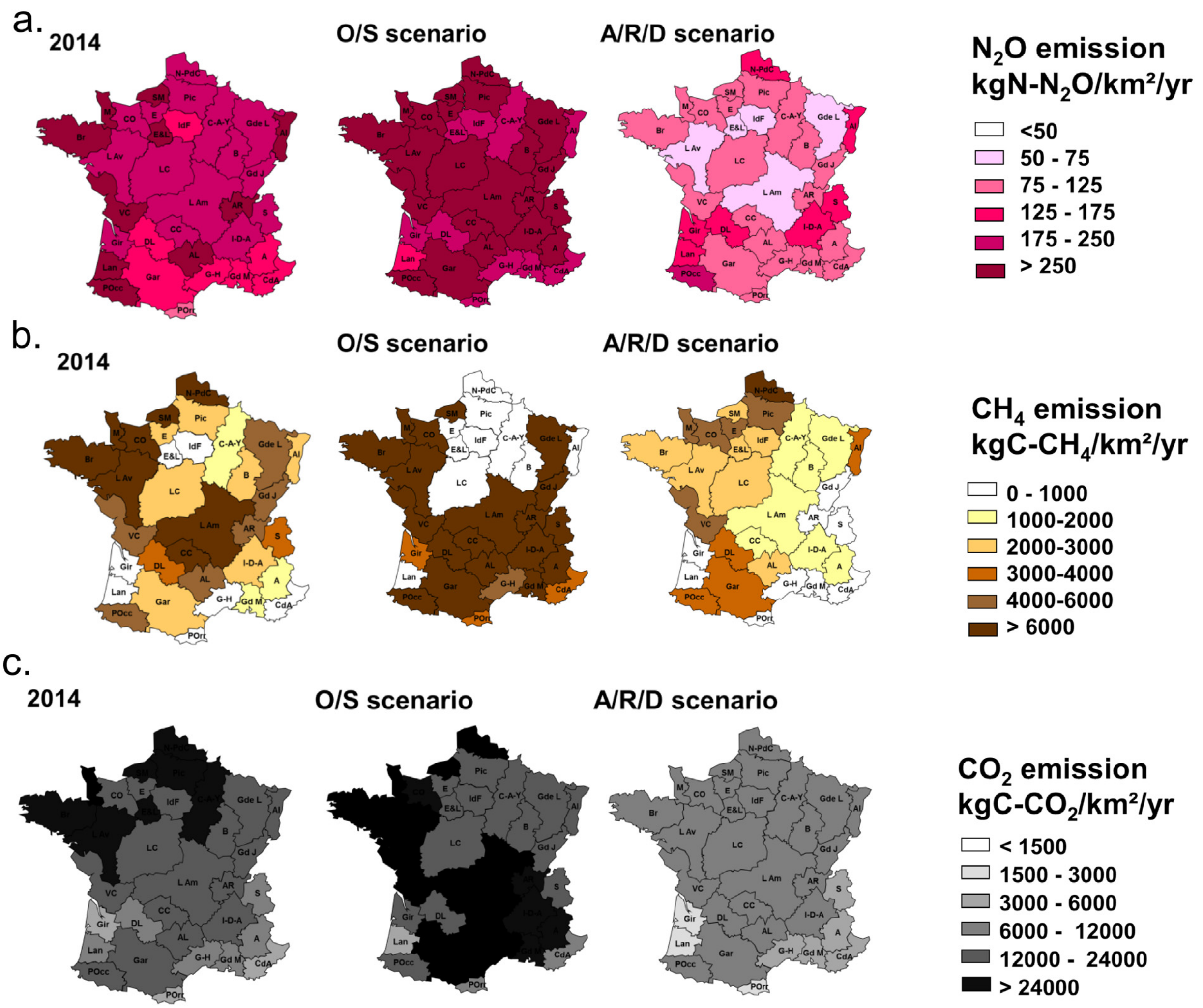

Fig. 6. Maps of regional distributions in France for present (2014) and for two prospective scenarios (O/S: opening and specialisation and A/R/D: autonomy, livestock reconnection and demitarian diet) of GHG emissions per km^2 and per year: a. N_2O; b. CH_4; c. CO_2. See legend of Fig. 4 for the names of the regions.

respectively, 265 and 28 times the CO_2 GWP using the 100-year GWP (IPCC, 2014). Total agricultural emissions for France amounted to 113,939 ktons CO_2 Eq yr^{-1} for the 2010s, with 49% CH_4, 29% N_2O and 22% CO_2 (Fig. 8a; Table 4). Regarding the three selected regions, similar in area, the Great West emissions were twice those of the other two, with the highest proportion in CH_4 (59%). N_2O emission dominated in the intensively cropped Seine Basin (37%) and CH_4 in the Great South-East (48%). Whereas the O/S scenario would increase overall GHG emissions almost 1.5 times for France, the increase would be about 1.2 for the Seine Basin and the Great West, but emissions would explode for the Great South-West with a 2.5-fold increase. With no mineral fertilisation and extensive livestock breeding, the A/R/D scenario would lower emissions by 50% for France, 36% and 76% for the Seine Basin and the Great West, respectively, but emissions for the Great South-West would only decrease by 11% (Fig. 8b–d; Table 4). Note that, taking into account a 20-year GWP, i.e., 265 for N_2O and 84 for CH_4 (IPCC, 2014), would double the total emissions at the scale of France, CH_4 then representing about 75% of the total for the 2010–2014 period, and up to 80% for both scenarios.

When expressed per km^2 of surface area, agricultural GHG emissions ranged from 148 to 408 tCO_2 eq km^{-2} yr^{-1} for the Great South West and Great West regions respectively, the GHG for the Seine Basin being close to the national value (Table 4). For comparison, agricultural GHG emissions were 3.4, 2.4, 1.3 times higher than the French ones for the Netherlands, Belgium and Germany, but 2.0, 1.8, 1.7, 1.6 times lower for Spain, Romania, Austria and Slovenia, respectively (EAA, 2018).

4. Discussion

Greenhouse gas emission estimates are known to be highly uncertain, due to the complexity of their controlling factors at the local scale and the difficulty of measuring them on-site as well as due to the lack of uniform information on how highly diverse farming practices may impact net GHG balances. Consequently, the scientific community is encountering problems formalising mechanistic models to estimate GHG emissions (e.g. NOE, DNDC, Gu et al., 2014; Gilhespy et al., 2014; Zimmermann et al., 2018), for upscaling local emissions measurements to larger scales, from local areas to countries. Since the level of detail needed for a wide regional and long-term estimation could make the modelling unfeasible, the approach used here is more a budgeting one, based on activity data from agricultural census and emission factors determined on a rather detailed analysis of the controlling factors of N_2O and CH_4. For these two GHGs, our calculations allow linking plot-scale measurements or animal physiology to the regional and country scale. CO_2 emission estimates are still rough, although explicitly taking into account several contributions, mostly upstream of the production system, but in line with the Climagri approach for France (Doublet, 2011) and other studies (e.g. Canada, Dyer and Desjardins, 2009, and Spain, Aguilera et al., 2015).

4.1. Controlling factors of GHG emissions

To explore strategies to reduce GHGs from agriculture, identifying, quantifying and understanding the factors which control their

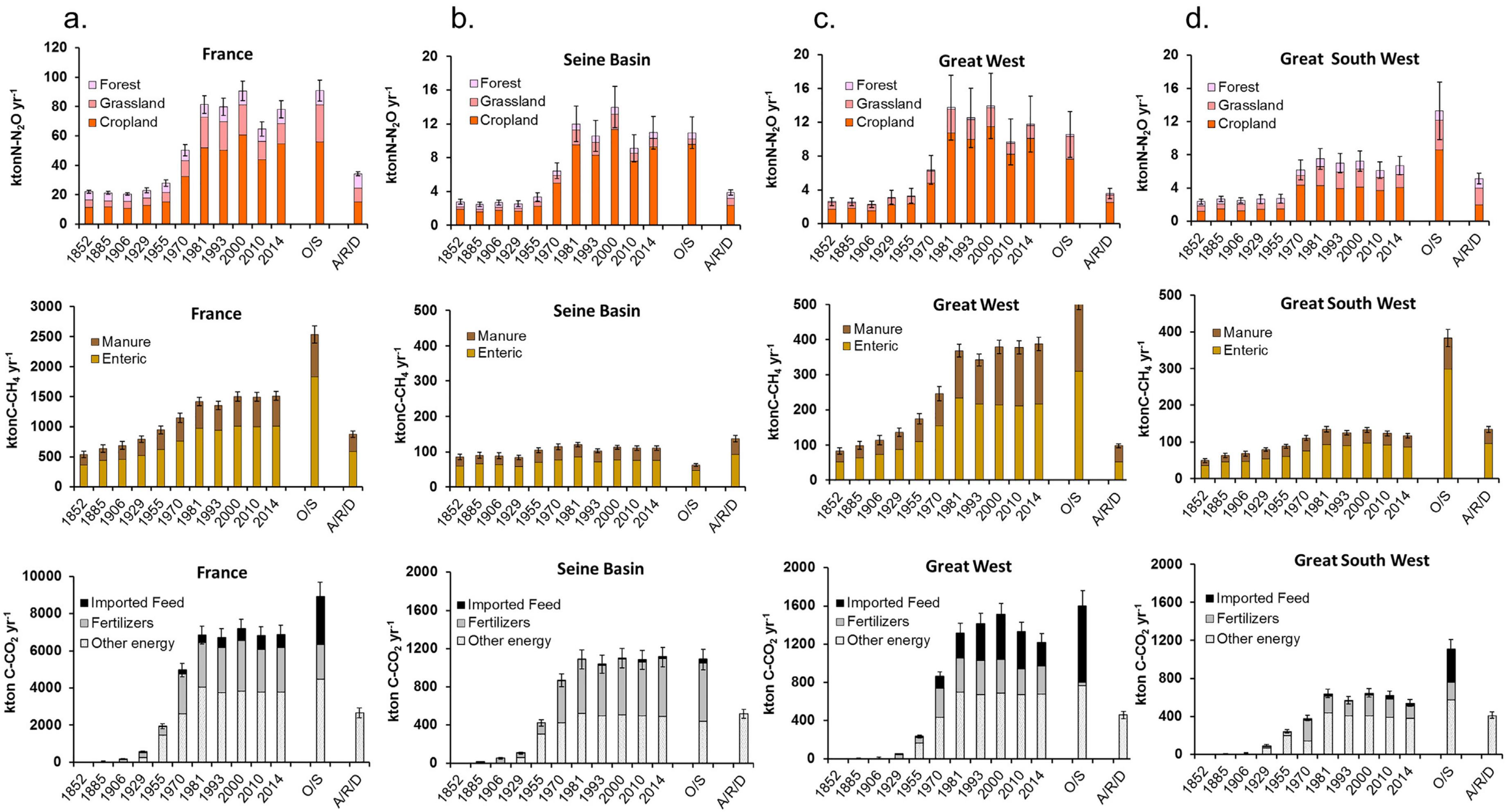

Fig. 7. Long-term evolution (1852–2014) for France (a.) and the three selected supra-regions (b., c., d.) in annual average of N_2O, CH_4 and CO_2 from top to bottom. N_2O is represented for the three major land uses (forest, grassland and cropland), CH_4 for manure and enteric emissions, and CO_2 as energy for imported feed, fertiliser production and other energy, including field work, machinery and livestock breeding. Error bars provide uncertainties as calculated by the Monte Carlo analysis.

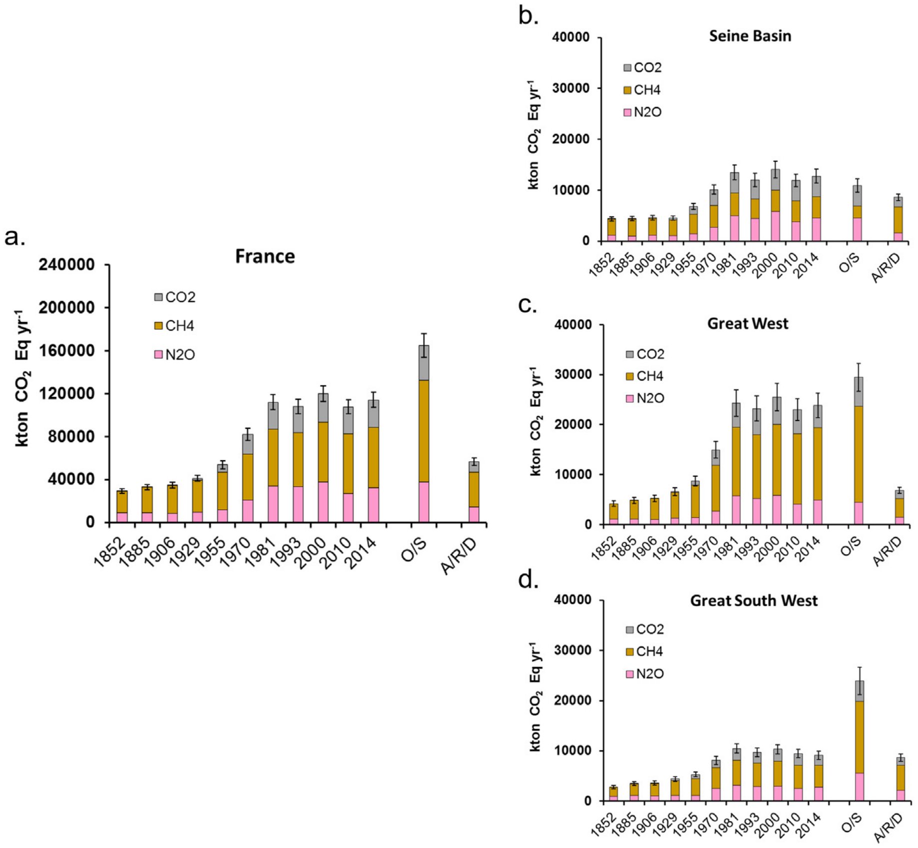

Fig. 8. Long-term evolution (1852–2014) for France (a.) and the three selected supra-regions (b., c., d.) in annual average of N_2O, CH_4 and CO_2, expressed in CO_2 equivalents per year. Error bars provide uncertainties as calculated by the Monte Carlo analysis.

producing processes, from biotic to abiotic, from microbial to industrial, are challenging.

4.1.1. N_2O

In temperate systems, denitrification is considered the major microbial process at the origin of N_2O emissions in soils, mostly under temperate and highly humid conditions (Benoit et al., 2015b; Vilain et al., 2014; Gu et al., 2014). In contrast, nitrification plays an important role in Mediterranean and semi-arid regions (e.g., Sanz-Cobena et al., 2012; Aguilera et al., 2013). The factors affecting denitrification in soils have been largely reported in the literature (see Tiedje, 1988; Groffman, 1991; de Klein et al., 2001, for example). Following Saggar et al. (2013), who distinguished two types of controlling factors, namely (i) soils and plant factors (crops, soil mineral nitrogen, pH, water content and oxygen, carbon availability, C:N ratios) and (ii) environmental factors (temperature, rainfall, drying/wetting vs freezing/thawing), the variables we considered for our prediction relationships (N input, land use and climatic conditions [temperature and rainfall]) covered these two types of factors. Generally considered to be the major controlling factors of N_2O production in soils, under both nitrifying and denitrifying conditions (e.g. Snyder et al., 2009; Smith, 2010; Kirschbaum et al., 2012; Sanz-Cobena et al., 2017), these variables are the best documented in the literature for achieving such a long-term study.

Table 4
Relative contributions of N_2O, CH_4 and CO_2 and total GHG emissions from agriculture in France and in the three supra-regions considered, given in CO_2 equivalent. Specific GHG emissions ($tCO_2\ km^{-2}\ yr^{-1}$) are provided for comparison.

CO_2 Eq		2000–2014	O/S scn	A/R/D scn
France 540,498 km^2	% N_2O	29	23	25
	% CH_4	49	57	58
	% CO_2	22	20	17
	$ktCO_2\ yr^{-1}$	113,939	165,010	56,678
	$tCO_2\ km^{-2}\ yr^{-1}$	211	305	105
Seine Basin 69,713 km^2	% N_2O	37	42	20
	% CH_4	32	21	62
	% CO_2	31	37	18
	$ktCO_2\ yr^{-1}$	12,909	10,872	8246
	$tCO_2\ km^{-2}\ yr^{-1}$	185	156	118
Great West 59,109 km^2	% N_2O	20	15	23
	% CH_4	59	65	57
	% CO_2	21	20	19
	$ktCO_2\ yr^{-1}$	24,123	29,471	6397
	$tCO_2\ km^{-2}\ yr^{-1}$	408	499	108
Great South-West 65,437 km^2	% N_2O	29	23	25
	% CH_4	48	60	59
	% CO_2	23	17	17
	$ktCO_2\ yr^{-1}$	9662	23,937	8582
	$tCO_2\ km^{-2}\ yr^{-1}$	148	366	131

Our approach is a step further in the use of the Tier 1 emission factor (IPCC, 2008), which has been found too coarse for correctly representing N_2O emissions possibly underestimated in wet areas (Lu et al., 2006 and reference herein) but overestimated in Mediterranean regions (Aguilera et al., 2013; Cayuela et al., 2017). The approach we developed here is advantageous for its low requirement in complex agronomic data, given that temperature and rainfall are routinely surveyed everywhere and fertilisation commonly quoted in agricultural statistics.

However, taking into account the annual scale of our study, pulses of N_2O emissions cannot be represented as observed after fertiliser applications (Bouwman, 1996; Hénault et al., 1998; Laville et al., 2011; Plaza-Bonilla et al., 2014; Benoit et al., 2015a; Recio et al., 2018), rainy events (Zheng et al., 2000; Lu et al., 2006; Beare et al., 2009) and during freeze and thaw periods and rewetting in semi-arid regions (Vilain et al., 2010; Lu et al., 2015; Wertz et al., 2016; Sanchez-Martín et al., 2010). However, the N_2O emissions data gathered here were selected for their annual representativeness, thus already integrating seasonal variability. Spatial and long-term variations can be expected through the heterogeneous distribution in both rainfall and temperature in the country (cf. Fig. 1a) and fertiliser applications depending on soil characteristics, which condition the technical orientations of the farms (cf. Fig. 1b). N_2O emissions related to manure management were not taken into account in the calculations, because they account for only a few percent of GHGs emitted from livestock, i.e., 2.94% in CO_2 Eq according to the review by (Zervas and Tsiplakou, 2012).

4.1.2. CH_4

Methanogenesis is a microbial process producing CH_4 mainly under anaerobic conditions. Enteric fermentation by grazing animals is the major process producing CH_4, although losses from manure management is far from negligible, far above the net CH_4 flux in the soil. Although agricultural soils can be a sink for this GHG, as a result of the balance between methanogenesis and methanotrophy (microbial CH_4 consumption) (Dutaur and Verchot, 2007; Kirschbaum et al., 2012), this function of oxidation by soils has been reduced with the intensive use of fertilisers. Ammonium inputs, increasing nitrifying activity, would exclude methanotrophs from their ecological niche, which even when fertilisation ceases would not quickly recover (Lemke et al., 2007; Ball et al., 2002; Boeckx and Van Cleemput, 2001; Schnell and King, 1994). In addition, soil cultivation and change in soil structure would restrict diffusion sites, thus affecting CH_4 oxidation (Dobbie and Smith, 1996). Experimental measurements in the Seine Basin showed that CH_4 removal could account for 5.6% of the emissions by livestock (Garnier et al., 2013). The CH_4 depletion rate was the highest for grassland soils (1.27 mg C m^{-2} d^{-1}) followed by forest (0.7 mg C m^{-2} d^{-1}) and cropland (0.4 mg C m^{-2} d^{-1}). Interestingly, the riparian zones, which were alternatively a source or a sink, overall emitted 0.1 mg C m^{-2} d^{-1} methane.

Considering the low proportion of CH_4 removal by soils compared to the emissions from livestock, even when it was half as much on average than currently for the long 1850–1950 period, we can consider that neglecting soil sink would not lead to overestimation of CH_4 emission in the past. Further CH_4 sink would account for about 2% of N_2O emissions from soils in CO_2 equivalents (Boeckx and Van Cleemput, 2001).

Enteric fermentation was estimated here to be responsible for 70% of CH_4 emissions in France, 30% originating from manure management, with a similar proportion over the time period studied, resulting in a proportion of enteric fermentation lower than the figure provided globally as being responsible for 83% of CH_4 emissions (Zervas and Tsiplakou, 2012). As reported by these authors, ruminant CH_4 production may depend on many factors including diet (fibrous content of the ration), enteric flora, while more generally CH_4 production is influenced by farm management and the farm production system.

In this study, we did not intend to finely characterise CH_4 production from livestock as reported in the study mentioned above (and references therein) but rather used the IPCC Tier 3 guidelines (IPCC, 1997), according to specific emissions (enteric and manure) for 19 categories of livestock and related to animal body weight over the period studied (see Material and methods section).

4.1.3. CO_2

An increasing greenhouse effect is currently dominated by the increase in CO_2 concentration derived from fossil-fuel consumption, clearly the compound responsible for the enhanced greenhouse effect (Forster et al., 2007). At the scale of the Seine Basin, CO_2 emissions account for 79% of the total emissions (agricultural and non-agricultural), 72% of which come from non-agricultural sectors (Marescaux et al., 2018). Similar figures were provided by CITEPA for France (i.e. 78% and 75%, respectively, in 2014 (https://www.citepa.org/fr/activites/inventaires-des-emissions/secten). Regarding the three GHGs, the CITEPA figures showed an approximately 20% underestimation for the agricultural sector (90,000 ktons CO_2 eq yr^{-1} versus 114,000 ktons CO_2 eq yr^{-1} here), due to an underestimation of CO_2, fertiliser production, and machinery manufacture, for example, accounted for in the industrial sector rather than the agricultural sector.

The coefficients from Doublet (2011) (Table 3) are quite comparable with other approaches (Bochu, 2006; Aguilera et al., 2015). For all of France, we showed that a large amount of CO_2 emissions (35%) is linked to the energy supply for production of commercial chemicals. CO_2 emissions from feed to livestock accounted for 10% for France, but 20% for the specialised Great West. These emissions are generally ignored in most studies, including national inventories. “Other energy” (i.e. fuel for farm fieldwork, electricity for on-farm operations and energy for machinery) appeared to be the largest emitter sector (55%). Farm machinery manufacturing energy, a significant part of total CO_2 emissions from agriculture (13% in 2014 with spatial differences) has been roughly taken into account in this paper, but could be included in future research with greater detail (taking into account for example the number of tractors and their power, etc.). This percentage is lower than the farm machinery percentage reported for US corn farms for all Canada, accounting for 15% of the direct CO_2 emissions in the US (Patzek, 2003) and 19% in Canada (Dyer and Desjardins, 2009).

4.2. Past long-term changes in GHG emissions: practice and land use changes

Agriculture in France until the late 19th and early 20th centuries was characterised by a traditional family-based agriculture, with low external requirements (mechanisation, electrical power, etc.). Whereas the number of farms was around 5.5 million during the second-half of the 19th century, this number decreased to 2.3 million in 1955, with an increase in the size of farms, although small ones still dominated. During this period, only slow changes occurred in terms of the indicators selected, however (see Fig. 3, exogenous fertilisers and livestock including horses). Accordingly, N_2O and CO_2 emissions remained rather stable while CH_4 increased slowly, due to a slow but general increase of livestock density within integrated crop–livestock farming systems.

A second period can be identified after WWII when indirect energy inputs in agriculture started, the war materials industry and chemicals being reoriented to agricultural goods (e.g., fertiliser production through the Haber-Bosch process and intensification of tractor manufacturing and other agricultural machinery). This initiated 3 decades of continuous growth with cheap fossil energy and expanding global food markets (Dyer and Desjardins, 2009). French farms decreased in number by a factor of five by 1980 (i.e. 1 million), intensified their production, with a strong dependence on mechanisation, industrial fertilisers, pesticides and imported feed. GHGs reached their maximum in the early 1990s, when the Rio conference (1992) alerted the world to the strong deterioration of the environment, including GHG emissions.

Despite continuing intensification and specialisation, the third period, from the mid-1990s to the present, showed a stabilisation in GHG emissions and even a tendency to decrease (N_2O especially, see Figs. 7 and 8). Even before the Rio conference (1992), the use of mineral fertilisers – a major driver for N_2O emissions – was reduced in France (see Lassaletta et al., 2014b), since the nitrate directive (91/676/CEE) was promulgated for water resource protection. At this time, the data show that ruminants were reduced by 10%, slightly more in the specialised Great West in livestock breeding (17%). During this period, the number of farms still decreased (664,000 in 2000, 452,000 in 2013), with small farms the most affected (Agreste, 2013). Between 1993 and 2014, we calculated a net loss of 1.2 million ha (1.53 million ha lost as permanent grassland and 0.33 million ha gained in cropland, with forested areas stable during this time).

Land use changes are reported to have modified the flux of CO_2, CH_4 and N_2O through altered biogeochemical processes (Forster et al., 2007; Houghton et al., 2012; Kirschbaum et al., 2012; Tate, 2015). For example, according to Kim and Kirschbaum (2015), conversion from natural forest to cropland or grassland would increase net emissions by 7.3 ± 0.6 or 5.9 ± 0.3 t CO_2 eq ha^{-1} y^{-1}, respectively, while conversion of cropland or grassland to secondary forest would decrease emissions by 5.3 ± 0.9 or 3.6 ± 0.7 t CO_2 eq ha^{-1} y^{-1}, i.e. figures on the same order of magnitude, although the delay in losses/recoveries might not be similar.

Between 1929 and 2014, 3.3 and 1.8 million ha of permanent grassland and cropland, respectively, have changed use whereas 7.7 million ha were gained as forested area, representing a total loss of 2.6 million ha of these total rural areas. We considered 1929 as the first date of French border stability after the Alsace and Lorraine regions were reattributed to France in 1918. Most of these land use changes were implicitly taken into account in our calculations. However, the possible loss of sink function by soils for CH_4 under increased fertilisation was not accounted for (Boeckx and Van Cleemput, 2001). We also did not consider wetlands as possible CH_4 emitters, which were lost after their conversion to agricultural and other land uses (Zedler and Kercher, 2005; Verhoeven and Setter, 2010).

4.3. Contrasting scenarios for a possible future

The scenarios (Billen et al., 2018) explored here for GHG emissions were inspired from prospective documents elaborated at different regional, national and European levels (Poux et al., 2005; Solagro, 2014; Poux and Aubert, 2018) and also took into account other published results for the global scale (Schmitz et al., 2012; Erb et al., 2016; Muller et al., 2017).

The pursuit of intensification and specialisation in the O/S scenario, despite taking into account the current regulations, would, at a national scale, increase GHG emissions as a whole, but also each of the three GHGs considered separately. Some regional differences would appear however. Whereas increased N_2O emissions would be generalized over the 33 regions, CO_2 and especially CH_4 would be lower in the regions dedicated to cereal production, with no livestock as predicted for the Seine Basin. In most other regions, livestock would increase CH_4 and its associated feed production would impact CO_2, in accordance with the approach. This scenario, although credible taking into account the current trends of opening the agro-food system (Le Noé et al., 2016), would not be desirable for the environment, and specifically here for GHG warming, as stated by the last, recently published IPCC report (2018). This economic desire for growth, which is highly dependent on the international market, facilitating trade exchanges, is fully present in political discourse. This vision of the future of French agriculture devoted to cereal exportation driven by powerful food sectors, animal production oriented to milk powder export in industrial breeding farms and a human diet with a high ratio of animal proteins is in line with many documents coming from professional farmer organisations as well as Harbour Authorities (CRAN, 2006; DREAL HN, 2014; Benhalima, 2015; HAROPA, 2015). Furthermore, the emergence of the bio-fuel industries (mainly ethanol from sugar beet and biodiesel from rapeseed) is a paradigm that agriculture will have to face in future decades, even for energy consumption of the farm itself. It is worth mentioning that in this O/S scenario, the livestock structure was kept constant, since French livestock is traditionally dominated by cattle, despite a trend, at the global scale, to shift animal production from ruminants to non-ruminants, which could possibly reduce CH_4 emissions and CO_2 from feed (Westhoek et al., 2014).

Contrary to this vision of France fully involved in globalisation, the A/R/D scenario (Billen et al., 2018) amplifies the weak signals observed in recent years, showing the emergence of a new relationship to nature for a sustainable development, from which proactive policies could emerge. Due to several food crises (e.g. the mad cow problems in 1996, dioxin contamination in 1999, the *Escherichia coli* outbreak in 2011, among the most publicised events), increasing numbers of consumers are demanding healthy food products. At the same time, farmers exposed to chemical products are concerned by health issues, victims either themselves or family members and neighbours.

In this context, the A/R/D scenario explores alternative agro-food systems which (i) generalise organic farming practices banning exogenous mineral fertilisers and pesticides, (ii) favour local supply and (iii) decrease animal protein consumption in the diet, while reducing food waste. Although not fully realistic over the short term, this scenario becomes desirable for the health of people and the environment. For this scenario total production of plant and animal products are reduced, but this reduction is compensated by a reduction in the demand associated with dietary changes (see Billen et al., 2018). The A/R/D scenario, despite requiring a deep structural change of the agro-food system, shows a significant reduction of GHGs, i.e. 50% for the French agricultural sector compared to the 2010–2014 period, more than one-third of the total reduction advocated. Interestingly, this scenario, beneficial in terms of GHGs, has also been shown to improve water quality and to prevent the risk of coastal eutrophication (Desmit et al., 2018; Garnier et al., 2018).

4.4. Weaknesses and strengths of the approach

Agricultural statistics have been rather well documented in France since the mid-19th century, at the scale of the French "départements" (Poisvert et al., 2017; Le Noë et al., 2018; see also Garnier et al., 2014, 2016 for local studies), and hence the entire country (Harchaoui and Chatzimpiros, 2018), and provide realistic pictures of the changes occurring in the agricultural sectors for indicators such as fertiliser inputs, crop production, livestock units, etc.

The estimate of GHGs from these data is more ambitious given that no statistics exist for the past at this regional resolution. The task was the most difficult for N_2O due to variability in the emission factors even for the present. Indeed, direct N_2O emissions in agricultural fields occur essentially with great spatial and temporal variabilities related to many factors (soil parameters, crop species, agricultural practices, rainfall and water management, amount and type of fertilisation, etc.; Lu et al., 2006; Bouwman et al., 2013; Cayuela et al., 2017). Here, taking into account the accompanying N_2O data in the literature, and the data available over the long term, previous N_2O data mining (Garnier et al., 2009) was enlarged for the main land uses (forest, grassland and cropland), gathering temperature, rainfall and fertilisation, three major variables that were analysed for the past. Even though soil parameters were often documented in the papers examined, they were not included due to the lack of a homogeneous description in the studies considered. Because grassland studies, similar to cropland, reported fertiliser applications either though external inputs or grazing animals, N_2O emissions for these two land uses were grouped under the same relationship. The relationship for forests was established with fewer data. Overall the evaluation of both relationships in terms of NRMSE and bias is quite good.

Regarding CH_4, the uncertainties may be more related to changes in the size of the animals over time, modifying the figures documenting CH_4 emissions from enteric fermentation and manure management for the present. By applying a factor of change on the basis of a reconstruction of excretion for the major types of animals, we can consider that CH_4 emissions from livestock farming must be robust for the past. CH_4 emissions and oxidation from soils were not taken into account given that soils are known to be low emitters (Garnier et al., 2013; Kandel et al., 2018), which must be true for the period studied, because ecosystems such as wetlands, ponds, etc. had already been considerably reduced in the landscape, for health issues and for conversion of these lands into cultivated areas (Zedler and Kercher, 2005; Verhoeven and Setter, 2010).

The estimates for CO_2 are more indicative, because we only took into account its emissions related to field and on-farm work, fertiliser use, CO_2 emissions from machinery and CO_2 emissions linked to feed imports, applying coefficients reported in the literature based on a full material flow analysis (Doublet, 2011; see also Aguilera et al., 2015).

However, the approach allows reflecting regional differences and, differently from an overall national estimate, provides a variable range of GHGs related to the details of specific characteristics and possible transitions for each region.

For the whole of France, our approach fits rather well with the national agricultural inventories (Doublet, 2011) reporting ~114,000 ktons CO_2 eq. yr^{-1} (2010–2014) emitted from agriculture versus ~103,000 ktons CO_2 eq. yr^{-1} (for 2006); the percentages we found for N_2O, CH_4 and CO_2 (29%, 49% and 22%, respectively) can be compared with the 39%, 44% and 17%, respectively, found in Doublet (2011). Interestingly, carbon sequestration by agricultural soils, amounting to 6200 ktons CO_2 eq. yr^{-1} for France (Le Noë et al., 2019), accounts for only ~5% of our GHG emissions.

5. Conclusions

An analysis of the controlling factors of GHG emissions (land use, rainfall, temperature) together with the GRAFS approach gathering key variables of the agro-food system at any temporal and spatial resolution (fertilisers, livestock, crop production, etc.) made it possible to estimate N_2O, CH_4, CO_2 emissions at the scale of France's 33 agricultural regions.

The period studied, from 1852 to 2014, showed that the increase of GHGs can be divided into three major periods: (i) a long period from 1852 to 1955 with family mixed crop–livestock farming systems still in effect, small in size with very little mechanisation, and emissions increasing from ~30,000 to 54,000 ktons CO_2 Eq yr^{-1}; (ii) a second period of modernisation of French agriculture after WWII, with an increasing dependence on mechanisation, industrial fertilisers, pesticides and imported feed, favoured by fossil energy at a relatively low monetary cost and expanding global food markets, a period corresponding the maximum of GHG emissions, which reached 110,000 ktons CO_2 Eq yr^{-1} in the 1990s and 120,000 CO_2 ktons Eq yr^{-1} in the early 2000s; (iii) and then stabilisation (around 114,000 ktons CO_2 Eq yr^{-1} for 2010–2014) related to the abandonment of government policies directly aimed at intensification, and their replacement by environmental regulations after the Rio conference (1992) and the following protocols (e.g., Kyoto in 1997), which prompted the countries of the world to control or decrease their GHG emissions to avoid the adverse effects of climate change. Progressive spatial specialisation was observed as early as 1906, with regions already characterised by cereal production in the Northern half of France, and in the South-West, others by livestock, such as Bretagne in the West, and still others with a typically low proportion of grasslands, such as in the Seine Basin. This specialisation had an influence on the distribution of emissions in terms of intensity and compounds.

The contrasting scenarios explored showed that a 50% reduction of GHG emissions in the agriculture sector could be achieved with a deep change in the structure of the agro-food system, whereas the pursuit of the present trends of specialisation and intensification associated with international trade, even applying the current environmental regulations, could increase the current GHG emissions by a factor of 1.5.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.01.048.

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