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Food and nutrient self-sufficiency in France: revealing hidden dietary and production vulnerabilities for healthier-sustainable diets

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Food and nutrient self-sufficiency in France: revealing hidden dietary and production vulnerabilities for healthier-sustainable diets.

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Abstract

France's advanced agricultural systems support high food production, yet the resilience of its nutrient supply under growing climatic and market pressures remains uncertain. This study assesses national and regional food and nutrient self-sufficiency, examining how production structures align with dietary needs. Using agricultural production and dietary datasets, we evaluate self-sufficiency across energy, macronutrients, and key micronutrients, and compare supply patterns with dietary reference values and EAT-Lancet targets. France is broadly self-sufficient in calories and macronutrients, supported by diverse plant and animal sources. However, adequacy for several micronutrients and unsaturated fats depends on a limited set of foods, such as fruits, vegetables, legumes, nuts, and seafood, often spatially concentrated and partly import-dependent. While consumption patterns are relatively uniform across regions, production is highly heterogeneous, creating regional disparities and localized dependencies. These findings reveal that apparent national nutritional sufficiency masks structural vulnerabilities and limits the transition toward healthier, plant-rich diets. Strengthening resilience will require coordinated shifts in both dietary demand and agricultural production to enhance the availability and regional balance of nutrient-dense foods.

Keywords : Food security, Nutritional adequacy, Dietary sustainability, Agricultural production, EAT–Lancet diet

Introduction

France benefits from abundant water and cropland resources together with favorable climatic conditions. These factors, combined with advanced technological capacities, precision agriculture, efficient resource management, and the relatively stable and comparatively high incomes of the farming population, have contributed to sustaining one of the most productive and adaptable agricultural sectors in Europe (Batini, 2019). However, as the second most populous country in the European Union, with more than 68 million inhabitants and the highest fertility, France faces substantial and growing domestic food demand (Solaz et al., 2024). At the same time, French agricultural production is increasingly exposed to climate-related risks, as warming trends and recurrent drought events threaten crop stability and reduce yields (Tramblay et al., 2020). These pressures are compounded by broader global vulnerabilities, including market volatility, trade disruptions and geopolitical tensions, that can affect access to foods and imported agricultural inputs (Mamassi et al., 2026).

Food and nutrient self-sufficiency refer to the ability of a territory (i.e., country, region or continent) to meet the dietary and nutritional needs of its population through local production. Assessing self-sufficiency at the local scale is increasingly important to strengthen food system resilience under climate, economic, demographic and geopolitical pressures. France represents a relevant case study due to the multiple documented threats to agricultural systems and local disparities between food production and demand. Moreover, in high-income countries such as France, achieving food and nutrient self-sufficiency is closely linked to the availability of a diverse range of food groups and macro- and micronutrient sources that can adequately satisfy the population's dietary and nutritional requirements (i.e., food and nutrient-rich diets) (Gazan et al., 2016; Bolo et al., 2026; Miller et al., 2022). In this context, assessing France's food and nutrient self-sufficiency requires evaluating both food groups and macro- and micronutrient self-sufficiency balances, as well as examining how different food groups contribute to each nutrient self-sufficiency metric under current population dietary patterns. Consequently, this provides a more comprehensive understanding of the national food system: its vulnerabilities (i.e., the national system's imbalances in ensuring adequate and stable supplies for specific food

groups and nutrients) and its resilience (i.e., the national system's capacity to maintain adequate provision for specific food groups and nutrients in the face disturbances).

Although a national food systems with high production potential can generate substantial nutritional surpluses (Berners-Lee et al., 2018), the effective availability of food and nutrients at the regional level depends on the interplay between the local production capacities. This includes elements such as natural resource endowments, region-specific dietary patterns, interregional trade and distribution networks, and broader administrative, social and economic structures that shape resource allocation, purchasing power and market access (Mamassi et al., 2026; Müller, 2026). The role of subnational assessments of food and nutrient self-sufficiency in strengthening food-system resilience remains less clearly defined. In France, several strategic and scientific arguments support evaluating self-sufficiency at regional administrative scales. First, enhancing food and nutrient self-sufficiency locally can increase resilience to systemic shocks, as illustrated by the COVID-19 pandemic, which exposed the vulnerability of highly centralized and globally interconnected food systems through lockdowns, regional isolation, supply-chain disruptions and trade restrictions (Li et al., 2021). Second, reliance on long-distance domestic transportation increases the risk of both quantitative and qualitative food losses (Erb et al., 2016; Parfitt et al., 2010); because of inadequate preservation, logistical inefficiencies, transport disruptions and infrastructure failures, while also contributing to environmental impacts such as energy demand and greenhouse gas emissions (Kesse-Guyot et al., 2022; Pradhan et al., 2014). Third, France's marked regional specialization; shaped by climate (Lungarska and Chakir, 2018), landscapes (Donfouet et al., 2017), and long-standing farming traditions (Billen et al., 2018; Le Noë et al., 2018), has produced distinct regional production systems resulting in unique food supply tendency and the potential for tailored nutrient-specific self-sufficiency profiles. Likewise, climate change might unevenly impact specific regions, altering rainfall, intensifying heat stress, and increasing extreme weather, particularly for staple and population significant foods (Le Roux et al., 2024). Finally, in recent years there has been a resurgence of interest and a host of initiatives in local food development plans, which help to bring production and consumption closer together, delivering local social benefits and fostering greater food democracy (IPES-FOOD, 2024). Together this regional heterogeneity underscores the need for localized food and nutrient self-sufficiency assessments and targeted adaptation

strategies (Mamassi et al., 2026; Pradhan et al., 2014). Overall, mapping regional production and nutrient balances can reveal patterns of surpluses and deficits, thereby informing strategies to optimize interregional food flows, manage logistical dependence and guide targeted policies that direct resources, investments and innovation towards sectors and regions with the greatest potential to strengthen nutrient self-sufficiency and environmental sustainability.

In this study, we present a comprehensive assessment of France's food and nutrient self-sufficiency, evaluated both at the national scale and across its twelve administrative regions, alongside an analysis of dietary diversity. Leveraging multiple datasets from diverse sources and applying a range of analytical approaches, we pursued three interrelated sub-objectives: **i)** quantifying food and nutrient self-sufficiency of France, **ii)** determining the relative contributions of different food groups to nutrients self-sufficiency and assessing overall dietary diversity, and **iii)** disaggregating self-sufficiency and diversity metrics at the administrative regional scale, thereby revealing spatially the regional heterogeneity and resilience in France's food system.

Results

France Nutrient Self-Sufficiency

Nutrient Self-Sufficiency Across the Two Dietary Profiles

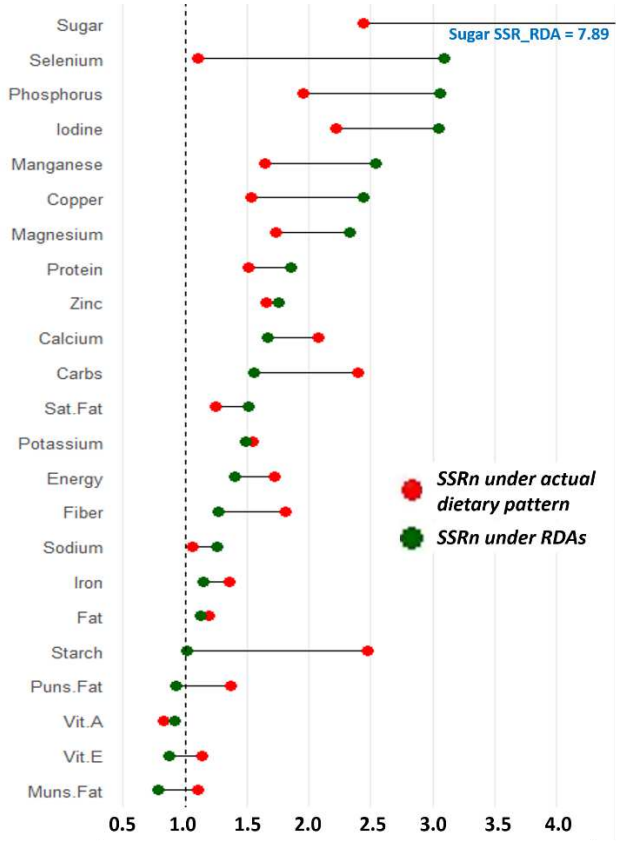


Fig 1. Nutrient self-sufficiency ratio *(SSR_n)* across dietary benchmarks: differences between the Recommended Dietary Allowances (RDAs) intake reference and actual dietary pattern of France population.

Integrating the national production data with the actual intake and with the RDA taken as a reference diet, France appears nutritionally self-sufficient for nearly all nutrients **(Figure 1a ; Table S1)**. When RDA is taken as intake reference, domestic production is in excess for total energy, protein, carbohydrates, dietary fiber, total fat, sodium and most minerals. However, production falls below the self-sufficiency threshold for mono- and polyunsaturated fats and for the fat-soluble vitamins A and E, with self-sufficiency ratios below 1 and reaching as low as 0.39. By contrast, when production is evaluated against the current French dietary pattern, all nutrients meet or exceed self-sufficiency. Particularly large surpluses are observed for sugars, sodium and several minerals, with self-sufficiency ratios generally exceeding 1.5 and reaching approximately 2-3 in some cases (e.g., carbohydrates, starch and iodine). Taken

together, these findings indicate that actual France's food system structurally oversupplies most nutrients while only marginally meeting current intake levels for key unsaturated fats and antioxidant vitamins (SSR_n < 1.2) and failing to reach sufficiency when defined by the RDAs (SSRn < 1).

Detailed results comparing the French population's dietary intakes (i.e., consumption levels) with recommended dietary allowances are provided in **Supplementary Results-Table S1.**

Food Groups Contribution and Diversity Display

Food Group Self-Sufficiency Under Actual French Diets and the EAT-Lancet

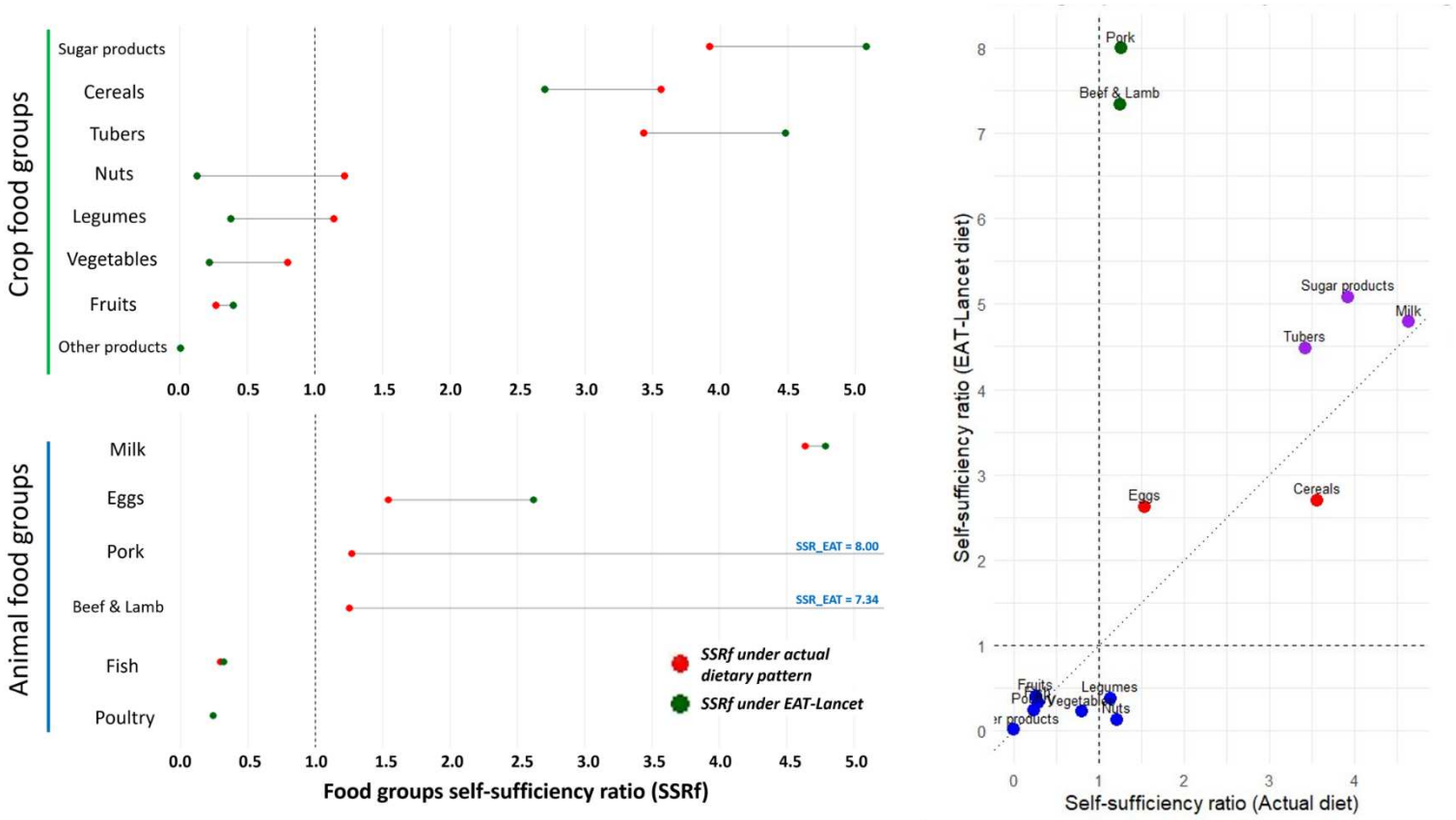


Fig 2. Food-group self-sufficiency (SSR_f) across dietary benchmarks: (a) shifts between actual dietary pattern and EAT–Lancet targets, and (b) clustering of food groups based on combined self-sufficiency profiles under both dietary scenarios.

Food-group self-sufficiency ratios expressed in food quantity terms show that France's domestic production markedly exceeds the actual demand for several staple and animal-source foods, while falling short for others **(Figure 2 ; Table S4)**. When benchmarked against France population's actual diets, production is more than threefold self-sufficient for

cereals and tubers ($SSR_f \approx 3.5$), sugar products (≈3.9) and milk (≈4.6), and remains comfortably above unity for legumes, nuts, beef and lamb, pork and eggs. By contrast, production does not fully cover current intakes of vegetables, fruits, poultry, fish and, most strikingly, some other crop products (e.g., vegetable oils), indicating a dependence on imports for these components of the present diet. Aligning demand with the EAT-Lancet reference diet substantially reshapes these patterns, amplifying existing surpluses for some groups while deepening or creating deficits for others. Under this healthier and more plant-forward dietary scenario, self-sufficiency remains high or increases further for cereals, tubers, sugar products, milk, eggs and especially red and processed meats, with SSRs for beef and lamb and pork rising to about 7-8 owing to the much lower recommended intakes. In contrast, the shift towards higher recommended consumption of vegetables, fruits, legumes, nuts, poultry and fish drives their SSRs well below one (down to about 0.13 for nuts and 0.22-0.40 for vegetables and fruits).

Clustering of food-group self-sufficiency ratios (SSR_f) expressed in quantity **(Figure 2b)**, jointly considering actual French dietary pattern and an EAT-Lancet compatible dietary scenario **(with similar patterns obtained when expressed in energy terms),** reveals four distinct configurations of food groups supply-demand balance. A first cluster groups fruits, vegetables, legumes, nuts, poultry and fish, whose SSR_f values remain below or close to unity under both benchmarks and decline further under the EAT–Lancet scenario, indicating structurally insufficient domestic supply for nutritionally critical food groups. A second and third clusters comprise staple commodities, including cereals, tubers, sugar products and milk, that consistently exceed the self-sufficiency threshold ($SSR_f > 2.5$) across both dietary profiles, reflecting a strong and persistent production surplus. In contrast, a fourth cluster encompasses ruminant and other animal products, notably beef and lamb and pork, characterized by moderate self-sufficiency under current consumption ($SSR_f < 1.5$) but very large surpluses under EAT-Lancet intake levels ($SSR_f > 7$), highlighting substantial overcapacity relative to the demand of a healthier, more sustainable diet. Eggs, although grouped within the third sufficiency cluster, display a similar pattern of moderate adequacy under current diets (SSR_f around 1.5) and increased surplus under EAT intake scenario ($SSR_f > 2.5$), suggesting their intermediate positioning between structurally balanced and over-supplied animal-source foods.

Taken together, quantity- and energy-based **(Supplementary Result-Table S4)** self-sufficiency indicators reveal a consistent structural pattern: France overproduces cereals, tubers, sugar products and most ruminant and dairy foods, while underproducing vegetables, fruits, legumes, nuts, poultry and fish relative to current dietary demand, with these imbalances becoming more pronounced under a transition towards EAT–Lancet-aligned, healthier dietary pattern.

Food Groups' Partial Self-Sufficiency ($PSSR_{f,n}$) within each Nutrient Spectrum

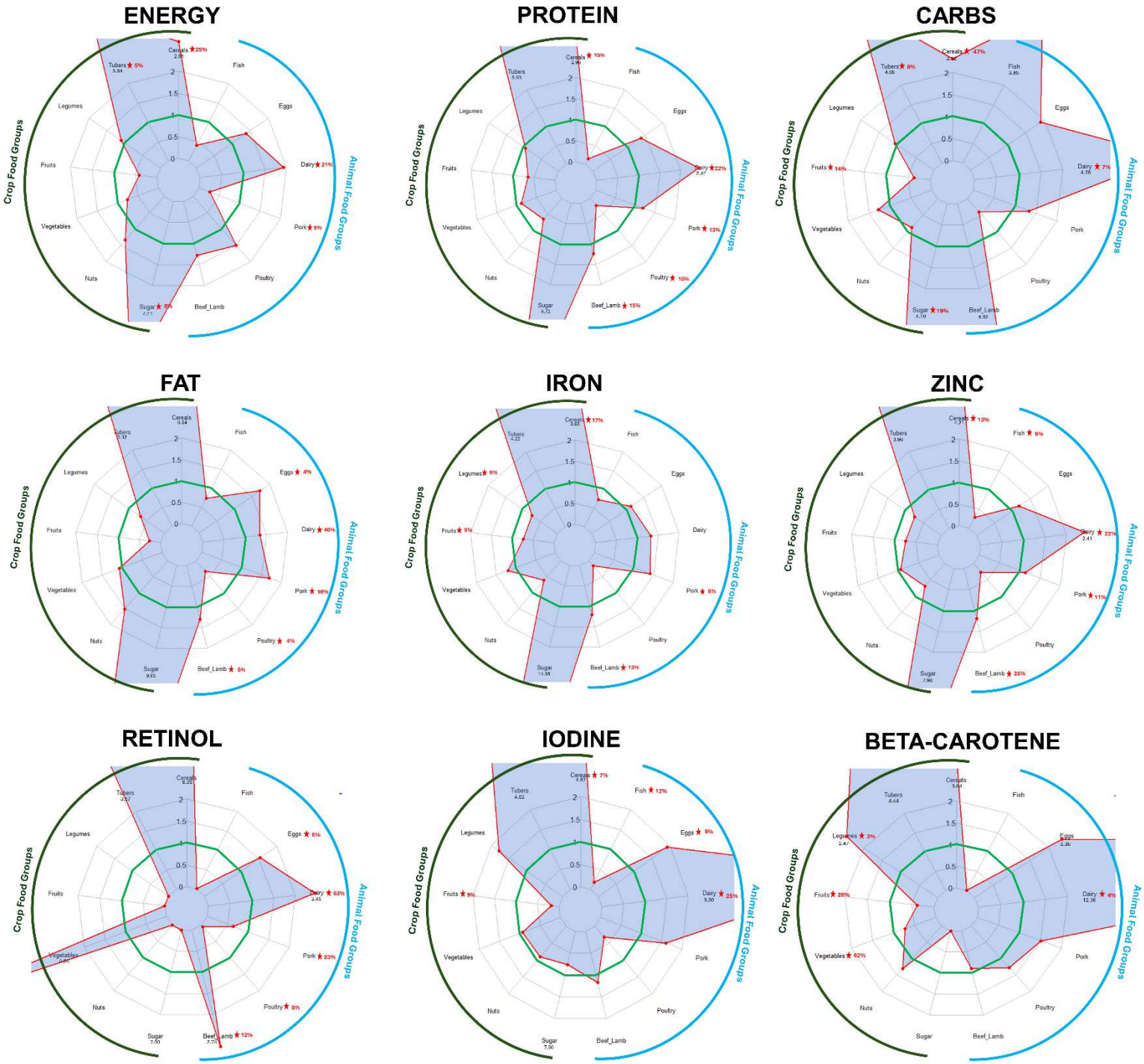


Fig 3. Food-group partial self-sufficiency for nutrients *($PSSR_{f,n}$)* in France, based on actual diet. radar representation of food-group partial self-sufficiency across nine selected nutrients **(full results for overall nutrients provided in Table S5)**. **The green reference** line denotes the sufficiency threshold (***$PSSR_{f,n}$*** = 1). **Red stars (★)** identify the dominant food groups in nutrient consumption, with **red values in parentheses** indicating their percentage

contribution among the five leading groups. **Black values** reported beneath food-group labels indicate cases of pronounced surplus ($PSSR_{f,n}$ > 2). ***As an example of how to read this figure,*** *poultry contributes to protein intake of French population (~30 g of poultry meat/day/capita), accounting for 10% of total protein consumption* (★)*, but exhibits low self-sufficiency (only 7 g are produced of poultry meat/day/capita), resulting in a low protein partial self-sufficiency (*$PSSR_{f,n}$ *= 0.22). Conversely, cereals contribute to protein intake (15%) due to high consumption (176 g of cereals /day/capita), and their high domestic production (626 g of cereals /day/capita) leads to a high protein partial self-sufficiency (*$PSSR_{f,n}$ *= 2.96). A* ***PSSR value*** *greater than 1 indicates that domestic production of a given food group can cover the amount of the nutrient currently consumed from that same food group; it does not imply that the food group alone can satisfy the total nutrient requirements of the population.*

The food-group level assessment reveals marked heterogeneity in the ability of individual food groups to achieve partial self-sufficiency within specific nutrient contexts **(Figure 3 ; details for the 24 nutrients in Table S5)**. **Cereals and tubers** consistently emerge as dominant pillars, exceeding partial self-sufficiency thresholds within each macronutrient, micronutrient, mineral and vitamin supply spectrum, thereby underpinning the structural foundation of the nutritional French diet. Among animal-source foods, **beef-and-lamb and pork meats** display similarly high performance, achieving or surpassing partial self-sufficiency across a broad spectrum of macronutrients and key micronutrients. **Dairy products** and, to a lesser extent, **eggs** also exhibit strong contribution, achieving high partial self-sufficiency within most of macro- and micro-nutrients, although their role remains limited for nutrients absent from these groups, notably fiber and starch. **Sugar products** follow a comparable pattern of achieving partial self-sufficiency within each macronutrient and micronutrient spectrum yet do not contribute to starch and vitamins adequacy (i.e., zero in the partial self-sufficiency ratio).

Detailed descriptive results on the relative contributions of food groups to; separately, the actual nutrients production and nutrients consumption are provided in **Supplementary Results-Tables S2 and S3**.

In contrast, several plant-based groups show more nutrient-specific and often constrained partial sufficiency. **Legumes** reach partial self-sufficiency within each of the major macronutrients (energy, protein and carbohydrates) but fall short across most

micronutrients' contexts, except only marginal adequacies within selected trace elements such as β-carotene, iodine and selenium. **Vegetables** occupy an intermediate position, with values clustering near the sufficiency threshold: they approach sufficiency (partial self-sufficiency ratio of 0.8 to 0.9) within the macronutrients contexts and meet or slightly exceed sufficiency within several micronutrients (0.9 - 1.2), reflecting their critical; yet not dominant, role in nutrient supply (i.e., low contribution in those nutrients consumption level). **Fruits** remain below the partial self-sufficiency threshold across the overall nutrient spectrum, despite making substantial contributions to the intake of iron, β-carotene, carbohydrates and iodine. In contrast, **Nuts** exhibit high nutrient efficiency, particularly for unsaturated fats and vitamin E, achieving partial self-sufficiency despite their relatively low contribution to overall dietary intake. **Poultry and fish** do not reach the partial self-sufficiency thresholds across the broader nutrient spectrum.

Taken together, these results highlight a dual structure of nutrient provision in the French food system, in which cereals, tubers and major animal-source foods (notably beef-and-lamb, pork, dairy and eggs) secure broad partial self-sufficiency across each of macro- and micronutrients supply, while other food groups play more targeted, nutrient-specific roles. Legumes, vegetables, nuts, fruits, poultry and fish primarily act as complementary contributors, helping to close specific adequacy gaps rather than independently ensuring partial self-sufficiency across the full nutrient spectrum.

Finally, **In Supplementary Result-Table S5,** we reported more detailed descriptive results on the structure and diversity of food group contributions to nutrient partial self-sufficiency.

Regional Patterns of Food and Nutrient Self-Sufficiency

Regional Patterns of Nutrient Self-Sufficiency Across France

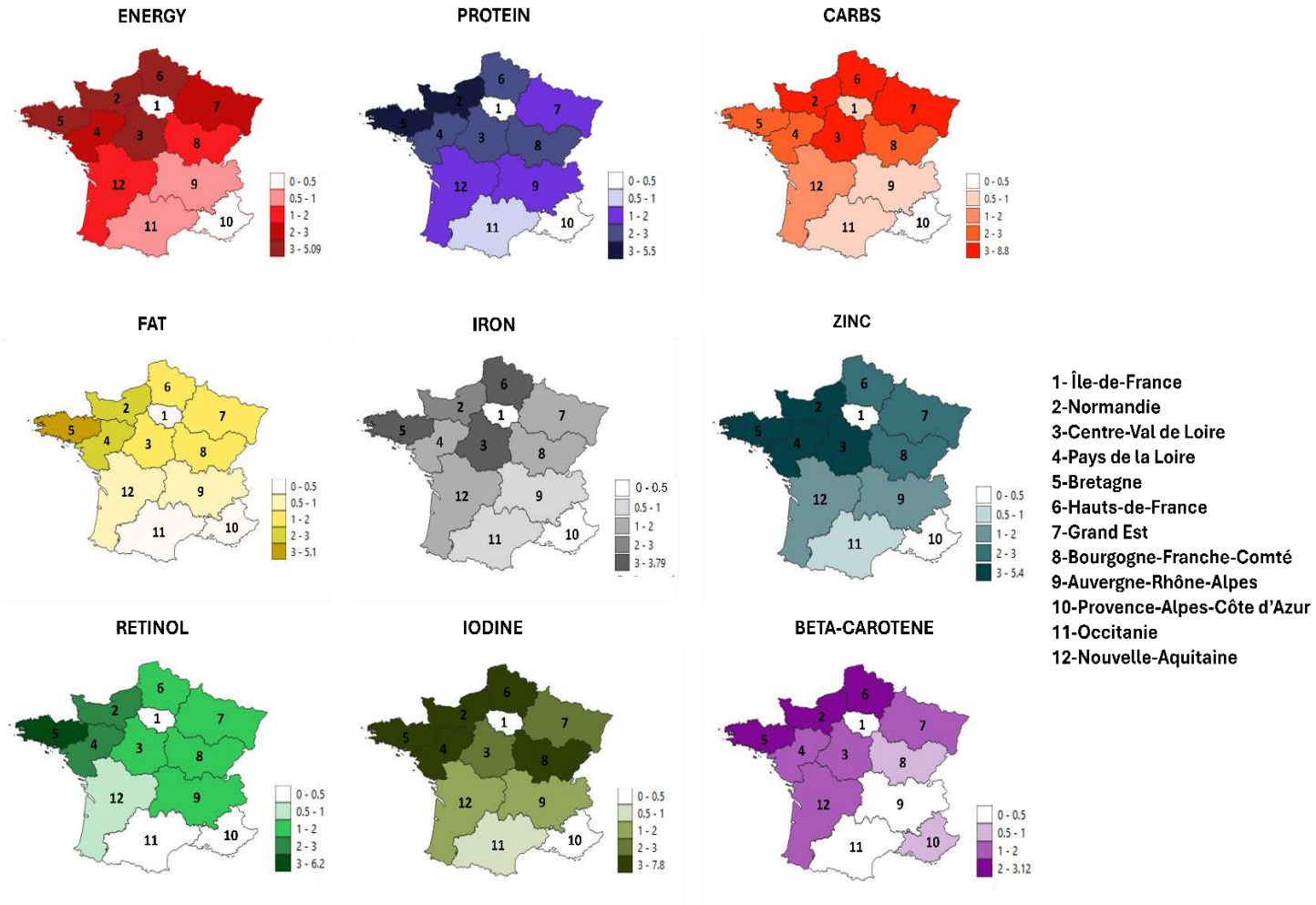


Fig 4. Regional nutrient self-sufficiency under actual intake benchmark: Spatial distribution of nine nutrient self-sufficiency across the 12 regions of metropolitan France **(full results for overall nutrients and under both intake profiles; actual intake and RDAs, are provided in Table S7).** Values are expressed as nutrient self-sufficiency ratio (SSRn), with color gradients indicating increasing levels of self-sufficiency from light to dark tones.

Detailed analyses of France's regional disparities under; separately, actual production and actual intake pattern, as well as their main drivers, are reported in **Supplementary Results-Table S6.**

Under both RDA- and actual dietary pattern based benchmarks, regions such as Normandie, Bretagne, Pays de la Loire, Hauts-de-France, Grand Est and Bourgogne-Franche-Comté exhibit high self-sufficiency ratios; often exceeding 2-3, for energy, protein, carbohydrates and several minerals **(Figure 4 ; Table S7).** These territories form France's principal cereal and livestock basins, combining extensive arable land with dense dairy, pig and poultry sectors. In

contrast, Île-de-France and Provence-Alpes-Côte d'Azur, Occitanie and to a lesser extent Auvergne-Rhône-Alpes, display ratios below 1 for several macro- and micronutrients, particularly when evaluated against actual consumption **(Figure 4)**. These regions pattern is aligned with their high population densities, competition for land with urban uses and a production structure oriented toward higher-value but less calorie-dense sectors such as horticulture and viticulture. Intermediate regions, including Centre-Val de Loire and Nouvelle-Aquitaine, generally, maintain clear surpluses for staple macronutrients but remain closer to balance for certain vitamins and trace elements, with self-sufficiency ratios around or only slightly above unity.

Across nutrients, an important subset consistently approaches or falls below the critical self-sufficiency band, indicating their potential vulnerabilities in the system. β-carotene represents the most pronounced case, with ratios below unity in nearly half regions and approaching balance only where fruit- and vegetable-rich production systems; particularly in western areas, partially offset local demand. Iodine and, in several regions, selenium also remain close to or below unity, reflecting their reliance on geographically concentrated supply chains centered on dairy, fish and certain animal products (i.e., north-western regions). For macronutrients, energy and protein are strongly in surplus in most western and northern regions but approach the critical range in more urbanized and Mediterranean territories. Unsaturated fats, especially polyunsaturated fatty acids, and several trace elements; including copper and zinc, also fluctuate around unity in some interior regions, suggesting limited redundancy in local supply.

Overall, no region achieves full nutritional self-sufficiency across all nutrients under either RDA-based or real-consumption benchmarks. Even the most productive regions such as Bretagne, Normandie and Nouvelle-Aquitaine; combine large surpluses for energy, protein, fats, calcium and phosphorus with deficits for at least one micronutrient, most frequently β-carotene or iodine. This indicates that, with such a regionalized production, intra-national trade in nutrient-dense foods remains necessary to balance regional supply. On other hand, Île-de-France and Provence-Alpes-Côte d'Azur remain below self-sufficiency for multiple nutrients and rarely reach clear surpluses even when evaluated only against RDAs, highlighting their structural dependence on inflows from surplus regions.

Regional Nutrient Supply Structure and Potential Food-Flow Resilience

Across regions, nutrient self-sufficiency is supported by markedly different combinations of plant- and animal-based food groups, revealing both relatively balanced and strongly specialized production structures **“Results Supplementary Material - Regions Results”**. In the western livestock belt (i.e., a geographic region in western France characterized by a high concentration of livestock farming, particularly dairy and beef production), including Bretagne, Pays de la Loire and Normandie, as well as parts of Nouvelle-Aquitaine, energy and protein self-sufficiency relies on a combination of cereals and very large contributions from dairy products, pork and other meats. Moreover, in these regions, animal-source foods supply most protein, fat, calcium and several trace elements, whereas crops dominate carbohydrates and dietary fiber. In contrast, north-eastern cereal basins, such as Hauts-de-France, Grand Est, Bourgogne-Franche-Comté and Centre-Val de Loire, exhibit more crop-oriented systems, where wheat and other cereals, sugar crops, oilseeds and legumes account for most energy, carbohydrates and several minerals, while animal products play a secondary but still important role for protein and fat. Mediterranean and mountainous regions, including Occitanie, Provence-Alpes-Côte d’Azur and Auvergne-Rhône-Alpes, exhibit a marked specialization in horticultural and fruit production, with fruits, vegetables and olive-derived products contributing substantially to vitamins, β-carotene and selected minerals, often approaching self-sufficiency levels. In contrast, cereals and animal-source foods play a comparatively limited role in total energy and protein supply, except in Auvergne-Rhône-Alpes, where mountain-based livestock systems sustain a more prominent contribution. As a result, these regions are characterized by predominantly plant-based micronutrient supply profiles but remain dependent on inflows of cereals and dairy products to meet staple requirements for energy, protein, fats and calcium. Île-de-France contrasts sharply, with a production system largely oriented towards cereals and sugar crops that remains insufficient to meet the demands of its dense urban population, and with limited livestock and horticultural output, leaving the region highly reliant on external territories for overall crop and animal food.

Linking regional nutrient self-sufficiency with food-group diversity shows that the resilience of France’s food system depends not only on aggregate production, but also on how many distinct food groups; crops and animal products, support each nutrient. Overall, robustness to shocks is greatest where high self-sufficiency coincides with both a large share of food

groups meeting partial self-sufficiency and a balanced plant-animal contribution; as in Bretagne, Pays de la Loire, Normandie and parts of Nouvelle-Aquitaine, and weakest in territories such as Île-de-France and some Mediterranean regions, where lower self-sufficiency levels are coupled with strong reliance on a few specialized groups (cash crops, or fruits and vegetables).

Discussion

Using national production data, our analysis indicates that France is broadly self-sufficient in calories and macronutrients both when considering actual nutrient intakes and RDA references. When evaluated against population's current consumption patterns, all nutrients meet or exceed self-sufficiency, with particularly large surpluses for sugars and sodium, which are nutrients whose intake should be limited. This profile aligns with documented dietary trends in France (Dubuisson et al., 2019), including high consumption of processed foods, excess salt intake and insufficient fiber, suggesting that the structural oversupply of energy-dense, nutrient-poor foods, although remixed with exports and imports, is effectively transmitted into diets, while micronutrient-rich foods remain comparatively under-represented. However, when assessed against RDAs, domestic production falls short for mono- and polyunsaturated fats and for fat-soluble vitamins A, β-carotene and E, with self-sufficiency ratios declining substantially. These findings indicate that recommended intakes for important nutrients cannot be met solely from domestic production. The literature has documented that many food systems worldwide achieve caloric sufficiency yet remain constrained by limited availability of micronutrient-dense foods, contributing to persistent forms of "hidden hunger" (Beal et al., 2017; Fletcher et al., 2024).

On the other hand, our results do not imply that France's lack of some nutritional self-sufficiency; specifically for micronutrients, translates into population-level nutritional insecurity. First, France is characterized by substantial reliance on imports that contributes to the intake of several micronutrients, including vitamins and unsaturated fats; particularly from legumes, vegetables, nuts and fish (Stehl et al., 2025). Second, production-based metrics as nutrient self-sufficiency (*i.e.*, the availability pillar) fail to capture inequalities in access and food affordability (*i.e.*, accessibility and stability) and within-country variation in dietary quality (i.e., utilization); the three additional pillars of nutritional security (Bahn et al., 2021; Molani-Gol et al., 2023; Mombert et al., 2025). Nonetheless, this low nutritional self-sufficiency when compared to recommended allowances indicates that the French production system as it stands is not able to sustain a move towards nutritionally adequate diets for the population, which reveals a lack of sovereignty capacity and a lack of resilience to geopolitical disruptions in trade.

At the food-group level, the structure of self-sufficiency reveals a clear alignment between surplus production and dominant sources of dietary energy as well as for other macro- and micronutrients provision. Cereals, tubers, sugars and red meat, which are produced in excess, are also the main contributors to national calorie supply, whereas food groups with production deficits, including fruits, legumes, nuts and fish, are those most critical for improving dietary quality and micronutrient intake. The observed production-consumption structure indicates that a transition towards healthier and more plant-forward dietary patterns cannot be evaluated independently of the current agricultural production structure. Because several food groups encouraged by dietary guidelines already exhibit relatively low levels of self-sufficiency, a dietary transition alone could increase the gap between domestic supply and recommended consumption unless accompanied by corresponding changes in agricultural production (Fischer et al., 2025; Springmann et al., 2020; Stehl et al., 2025). Under full adoption of the EAT-Lancet reference diet (Willett et al., 2019), the higher recommended intake of currently under-supplied food groups would reveal pronounced deficits, with self-sufficiency ratios falling well below unity. Addressing these gaps would require either increased reliance on imports or significant reconfiguration of domestic production systems, including shifts in land use, resource allocation and policy support. These findings are consistent with broader European evidence showing that alignment with health-oriented diets entails reducing animal-source production while much expanding fruits, vegetables and pulses, with important implications for agricultural systems and resource use (Rieger et al., 2023; van Selm et al., 2022). In In the French context, policy instruments such as targeted subsidies for horticultural and pulse production under the Common Agricultural Policy (CAP) have sought to address these gaps, although their effectiveness remains debated, highlighting the need for more coordinated and targeted food-system interventions (Prosperi and Kleftodimos, 2021). More broadly, the mismatch identified here between current agricultural production patterns and health-optimized diets underscores a wider structural challenge: most contemporary agricultural-food production systems remain misaligned with nutritional and sustainability targets, pointing to the need for integrated policies that jointly address agricultural production, trade and dietary-nutritional guidelines rather than treating them as purely consumer-side aspirations (Springmann et al., 2020; Stehl et al., 2025; Willett et al., 2019).

Linking nutrient self-sufficiency to food-group contributions reveals a marked asymmetry in the structure of France's food system. Most macronutrients are supported by multiple, partly redundant food groups, with complementary roles of plant- and animal-based sources providing buffering capacity against sector-specific shocks. In contrast, several micronutrients depend on a narrower set of specialized sources, increasing vulnerability in the food supply. This pattern is reinforced by diversity metrics, which show that while a relatively broad portfolio of food groups underpins macronutrient self-sufficiency, micronutrient adequacy relies on more limited combinations. Such findings are consistent with global evidence indicating that food systems are generally resilient for energy and macronutrients but more fragile for micronutrients due to reliance on a small number of nutrient-dense foods (Arimond et al., 2010; Kennedy, 2009). Consequently, reductions in diversity of the contributors to self-sufficiency, particularly among micronutrient-rich groups, would have limited impact on calorie availability but could rapidly compromise adequacy for nutrients such as calcium, iodine, selenium, vitamin E and provitamin A (Beal et al., 2017; Nicol et al., 2022). From an agricultural systems perspective, this imbalance underscores the need to diversify production beyond calorie-dense staple crops such as cereals and other high-energy commodities. While fortification and biofortification can partially address specific deficiencies, sustaining micronutrient adequacy ultimately depends on expanding the supply of currently under-represented, nutrient-dense food groups, particularly legumes, vegetables, nuts and seafood, using targeted reallocation of resources and investment (Fischer et al., 2025; Stehl et al., 2025; Yilmaz and Yilmaz, 2025). As an analogy for the effect of food diversity at the level of population diets, it has been shown that diversity is beneficial to nutritional adequacy when it operates within healthy food groups and when it results in increased consumption of subgroups that are sufficiently high in nutrients that are lacking and sufficiently low in nutrients to limit, thereby exerting a leverage effect on diet quality (Bolo et al., 2026). From a food policy standpoint, these findings indicate that demand-side dietary guidance alone is insufficient to drive meaningful nutritional transitions. Aligning France food production with health and sustainability objectives will require coordinated supply-side measures, including subsidy reform and strategic support for horticulture, pulses and sustainable aquaculture, to better match agricultural output with nutritional needs (Prosperi and Kleftodimos, 2021; Sirot et al., 2011).

Regional consumption patterns in France are relatively similar at an aggregate level, with only limited variation across territories. In contrast, agricultural production exhibits pronounced spatial heterogeneity, leading to substantial differences in self-sufficiency ratios across regions. Western and northern livestock-cereal regions generate substantial surpluses of staple calories, protein and minerals often exceeding an order of magnitude in major production basins such as Bretagne, Pays de la Loire and Hauts-de-France, whereas urbanized and Mediterranean regions (e.g., Île-de-France and Provence-Alpes-Côte d'Azur) exhibit persistent deficits and remain structurally dependent on inflows (Pecher et al., 2024; Rouxelin et al., 2022). These disparities reflect the combined interaction between achieving food self-sufficiency objectives and land competition, population density and regional specialization (Mamassi et al., 2025): highly urbanized, densely populated regions, as well as oriented regions towards higher-value but less calorie-dense sectors (e.g., Mediterranean regions); such as horticulture and viticulture, remain structurally dependent on inflows from other territories. Moreover, this asymmetry highlights that France's national self-sufficiency is structurally sustained by a small number of highly productive territories (Shi et al., 2021). This pattern mirrors broader European trends, where biophysical constraints; particularly soil and climate conditions, interact with socio-economic factors to shape pronounced regional heterogeneity in food production and nutrient balances (Lampach et al., 2025; Mamassi et al., 2026; Pecher et al., 2024).

At the same time, current study regional assessment has revealed important nutrient-specific vulnerabilities that are independent and not apparent at the national scale: **i)** while northern and north-western regions appear robust for energy and major minerals, their supply of carotenoids, vitamin E and certain essential minerals (notably iodine and selenium) depends on the limited number of specialized production areas, including southern horticultural systems and coastal fisheries; **ii)** the nutrient adequacy is further conditioned by the balance between plant- and animal-based production systems: regions combining strong cereal and livestock sectors (e.g., Normandie) benefit from complementary nutrient profiles, whereas more specialized regions risk shortfalls without interregional exchanges (Iachkine et al., 2026). Diversity metrics reinforce this pattern, showing that resilience is highest where high self-sufficiency coincides with diverse and balanced food-group contributions (e.g., Bretagne, Nouvelle-Aquitaine), but weaker in regions reliant on a narrow set of local commodities, such

as Île-de-France or Provence-Alpes-Côte d'Azur. Recent shocks, including disruptions linked to COVID-Pandemic and the war in Ukraine, further illustrate how dependence on interregional flows can amplify systemic risks under climate extremes or input shortages, underscoring the need for more spatially diversified and regionally adapted food-system strategies beyond aggregate national metrics (Accatino et al., 2022; Li et al., 2021; Mamassi et al., 2026).

Overall, France's food system is characterized by strong interregional complementarity, with distinct production zones collectively sustaining national nutrient supply. Cereal basins such as Hauts-de-France, Grand Est and Centre-Val de Loire primarily provide staple calories, starch, fiber and minerals to deficit regions, while western livestock areas; including Bretagne, Pays de la Loire, Normandie and Nouvelle-Aquitaine, export dairy and meat products that underpin national supplies of protein, fats and key micronutrients. Southern and mountainous regions, notably Occitanie, Provence-Alpes-Côte d'Azur and Auvergne-Rhône-Alpes, contribute disproportionately to the supply of fruits and vegetables rich in carotenoids and vitamins (Le Noë et al., 2018). This spatial organization supports national self-sufficiency but relies on continuous interregional flows that would become critical under constrained trade conditions, while simultaneously increasing exposure to transport and logistical disruptions (Kaufmann et al., 2022; Pecher et al., 2024). Also, despite achieving aggregate self-sufficiency, structural imbalances persist: surpluses in cereals and animal products coexist with deficits in fruits, vegetables and fish, and reliance on external inputs such as imported feed and fertilizers limits true territorial autonomy. Model-based evidence indicates that reconfiguring production by regional crop-livestock integration and targeted land reallocation could enhance resilience, reduce input dependence and better align supply with healthy dietary patterns, although projected climate pressures; particularly increasing water stress in southern regions, may weaken this complementarity, highlighting the need for adaptive diversification and integrated territorial strategies that align national dietary transitions with regional production capacities and constraints (Accatino et al., 2022; Mamassi et al., 2026).

In summary, France's food system emerges as broadly self-sufficient in calories and macronutrients, yet structurally vulnerable for several key micronutrients and for transitions towards healthier, plant-forward dietary patterns. While multiple plant- and animal-based food groups redundantly secure energy and protein supply, a much narrower portfolio of

specialized foods (e.g., legumes, fruits and vegetables, nuts and seafood), often spatially concentrated and partly import-dependent, underpins adequacy for unsaturated fats and micronutrients such as zinc, iron, copper, iodine, selenium, vitamin E, β-carotene and retinol. This configuration sustains an apparent national “nutritional self-sufficiency” under current, energy-dense consumption patterns, but conceals exposure to trade disruptions, market volatility and persistent inter-regional inequalities in access.

By integrating national and regional self-sufficiency metrics with food-group contributions and dietary diversity, this study shows that aligning French food production with health-optimized and sustainable diets; an objective for a higher sovereignty and sustainable food system, would require more than demand-side dietary shifts. Expanding the domestic availability of nutrient-dense foods would likely involve substantial reorganization of agricultural production systems and strategic supply-side transformations foods, while maintaining regional complementarity and resilience under climatic and market pressures. More broadly, these findings reinforce growing evidence that contemporary food systems are largely calorie-secure but micronutrient-fragile, all the more as the systems are considered at a fine granular level, highlighting detailed lack of resilience. Overall, our analysis indicates the need for integrated policy frameworks that simultaneously govern agricultural production, trade and dietary guidelines.

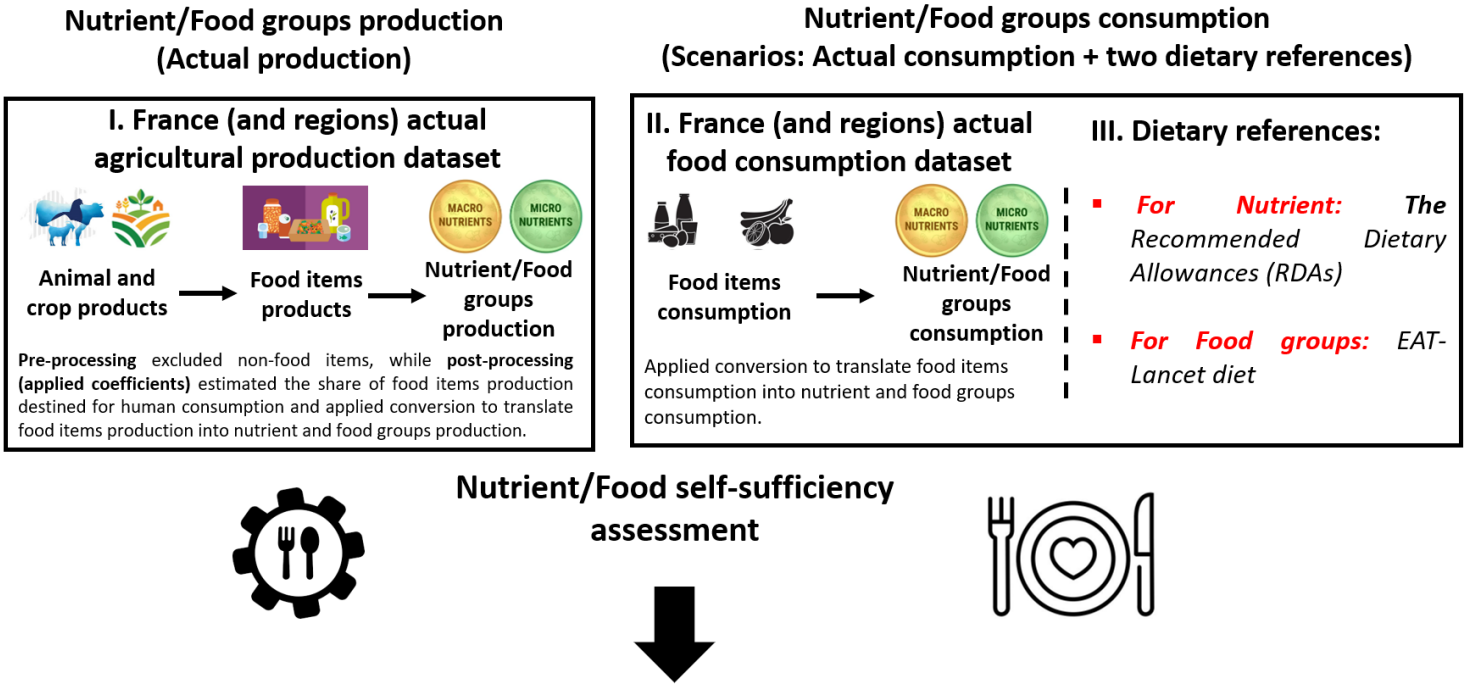
Methods

Study Area: France and the associated twelve administrative regions

France stands as the leading agricultural producer in Europe, and in the present study, we assessed the France food and nutrients self-sufficiency levels, along with the analysis of food diversity display. The analysis was conducted at two scales: at the national level, focusing exclusively on metropolitan France “closed hexagon” while deliberately excluding overseas territories; and at the regional level, considering the twelve administrative regions within metropolitan France. Restricting the study to this geographically contiguous area enables a clearer interpretation of internal food and nutrient flows by avoiding the complexities introduced by overseas departments, which are often located in distinct agro-ecological zones (e.g., the Caribbean, Indian Ocean, or Pacific). Furthermore, this spatial delimitation allows for more precise and context-specific assessments of food and nutrients self-sufficiency, infrastructure, and resource allocation, all of which operate under a unified logistical and administrative framework.

Methodology Overview

Given the extensive dataset types, their processing and the diversity of analytical procedures involved; including the equations, task-specific assumptions at each stage and calculations, the methodology presented in the main text is grounded in a comprehensive set of **“Methodology-Calculations Supplementary Material” file.** These supplementary documents provide detailed, task-specific methodologies tailored to each major component of the study.



IV. Data analyses

- Calculate France's **nutrient and food groups self-sufficiency ratios.**
- Quantify **food group contributions (partial self-sufficiency) to each nutrient and assess dietary structure and diversity under each nutrient (= highlights on vulnerabilities and resilience of food system at national level).**
- Evaluate the regional patterns of each **nutrient self-sufficiency across France's regions.**

Fig 5. Overview on the methodological framework

These tasks were organized in a logical sequence, beginning with the treatment of raw data and culminating in targeted analyses designed to extract meaningful results **(Figure 5)**. The first axis focused on processing actual agricultural production data in France and regions **(see section "Agricultural production").** The second axis centered on consumption data, which involved two major components: **i)** the treatment of actual food consumption data in France and regions **(see section "Food and nutrients actual dietary consumption")**, and **ii)** the integration of two normative (or reference) dietary benchmarks **(see section "Dietary references for food and nutrients healthy recommendations")**.

Building on these data sources, we conducted series of analyses **(see section "Data Analyses")**, aimed at evaluating nutrient and food and nutrient self-sufficiency levels, quantifying the relevant contributions of various food groups, and assessing dietary diversity. These assessments were carried-out through national as well as at regional level to capture spatial variation in food system resilience.

Production & Consumption Dataset

Agricultural production

Data on gross production of both crop and animal products were obtained from the "Agreste" database (https://agreste.agriculture.gouv.fr/agreste-web/), the official statistical system of the French Ministry of Agriculture. The raw data used in this study correspond to the recent available complete agricultural campaign (2022) and are provided at multiple spatial scales, ranging from the smallest agricultural zones up to departments, the 12 administrative regions of France metropolitan, and the national level. For the purposes of this analysis, we focused on the regional and national dataset. The dataset comprises two primary components: **i) crop production data**, including yields and cultivated areas across a range of crop types; encompassing both food and forage crops, from which total crop production was calculated; and **ii) livestock data**, detailing the number of animals by species and production category. All values represent gross production and therefore require both pre- and post-processing to isolate the fraction relevant to and effectively contributing to human nutrition. **Pre-processing** involved the exclusion of crops with exclusively non-food uses, such as feed-forage cereals, feed grasses, and crops classified as industrial (non-edible) products. **Post-processing** included the application of *"partial allocation coefficients"* to estimate the share of each crop ultimately destined for human consumption. For livestock, additional steps were implemented to convert herd inventories into net edible production of animal products. Finally, the conversion from agricultural products to nutrients was performed using nutritional composition data mainly comes from the Ciqual&CALNUT database (https://www.anses.fr/en/content/ciqual-nutritional-composition-table). USDA Food Data Central (https://fdc.nal.usda.gov/) (McKillop et al., 2021), is used as a complementary database to extract the conversion factors for products not included in previous sources. The document titled **"Method overview - details on production database"; integrated in the file of Methodology-Calculations Supplementary Material,** provides the description of the methodological steps, assumptions, and conversion factors employed to derive net food and nutrients production values used in the present analysis. Moreover, in the same file, all calculations are fully documented in an accompanying Excel document **"Annex 1 - Agricultural production calculations"**, which transparently presents

the underlying data and processing logic. All reference sources used to inform conversion factors and nutritional composition are also included in last document.

Food and nutrients actual dietary consumption

Data on actual dietary pattern were derived from the INCA3 survey (Individual National Study of Food Consumption) the third national dietary study conducted by ANSES (French Agency for Food, Environmental and Occupational Health & Safety). Carried out between 2014 and 2015, INCA3 provides the most recent representative dataset on the food consumption patterns and dietary habits of the French population and serves as a key national reference for dietary assessments. This robust dataset enables the estimation of habitual dietary intake per food items and at the individual level by accounting for day-to-day variability in food consumption. While the INCA3 data reflect dietary behavior from 2014-2015, the present study assumes that general dietary patterns have remained sufficiently stable to justify their application in conjunction with the 2022 production data. This assumption supports the evaluation of food and nutrient self-sufficiency levels and the diversity of nutrient availability at both national and regional scales. Methodological processing steps were required to estimate the actual consumption of an average individual in France and each region. Using the INCA3 survey data, we first calculated the mean daily consumption of each food item for adults aged 18-79 years. To derive population-wide estimates, these values were then adjusted to account for the dietary intake of other demographic groups; children and adolescents (0-18 years) and the elderly (65+ years), based on their relative energy requirements (ANSES, 2016). This adjustment was applied at both national and regional scales. Specifically, the average daily consumption of each food item (expressed in g/day per individual per region) was estimated by combining adult consumption data with scaling ratios that reflect the energy-adjusted intake of each sub-population, weighted by the demographic composition of each region. As the production component, the conversion from food consumption to nutrient consumptions was conducted using nutritional composition data mainly comes from the Ciqual&CALNUT database. Proxies from USDA Food Data Central database were used for the conversion of food not included in the previous source. **The Methodology-Calculations Supplementary Material file include a document entitled "Method Overview on Consumption Database"** and that details the methodological steps, assumptions, and formulas used to estimate per

capita consumption in France and its regions. All data and processing logic are transparently documented in an accompanying Excel file **“Annex 2 - Food & Nutrient consumption calculations”**.

Dietary references for food and nutrients healthy recommendations

This study employs two categories of global dietary reference frameworks to benchmark and to be compared with the actual dietary patterns in France and across its regions, including assessments of self-sufficiency and dietary diversity: the Recommended Dietary Allowances and food-based dietary guidelines “EAT-Lancet diet”.

The Recommended Dietary Allowances (RDAs) includes the nutrient recommendations: nutrient intake recommendations, including those for energy, protein, and a broad spectrum of micronutrients, were derived primarily from age-specific reference values. Where applicable, additional sub-criteria such as sex, body weight, physical activity level, basal metabolic rate, and specific physiological requirements were incorporated for certain nutrients (e.g., body weight for protein). These recommendations were informed by authoritative international sources, with priority given to reference tables and reports from the World Health Organization (WHO), the Food and Agriculture Organization (FAO), the National Institutes of Health (NIH), and other global health agencies. **The Methodology-Calculations Supplementary Material file integrate a document titled “Method overview on RDAs”** provides the description of the methodological steps and the criteria employed to derive nutrients intake recommendations based on RDAs. The calculations were conducted in the Excel **“Annex 3 - Nutrients RDAs calculations”.**

Food-based dietary guidelines are exemplified by **the EAT-Lancet reference diet**, which provides a quantitative framework for healthy dietary patterns that promote both human health and environmental sustainability. It specifies target intake ranges for major food groups (not nutrients), such as whole grains, fruits, vegetables, legumes, nuts, dairy, and animal-sourced foods, expressed on a per-capita, daily basis. These targets are grounded in epidemiological evidence linking diet composition to reduced disease risk, while also aligning with planetary boundaries for land use, water consumption, and greenhouse gas emissions (Kesse-Guyot et al., 2022; Willett et al., 2019). In this study, the EAT-Lancet dietary targets served as a food-based benchmark were defined directly in the **Results Supplementary**

Material file, **in "Annex 4"** and were used for evaluating national food self-sufficiency under a healthy diet, and for comparing these targets with actual dietary patterns.

Data analyses

Building on the integrated dataset derived from production, consumption, and dietary reference sources, we performed targeted analyses to evaluate multiple dimensions of France's food system. This multi-level analytical approach allowed for both a national overview and a finer-grained understanding of regional disparities in France food system performance.

Nutrients' self-sufficiency level

Nutrients' self-sufficiency was quantified using the indicator of self-sufficiency ratio (SSR_n), which measures the extent to which domestic production can satisfy population demand for a given food group or nutrient:

$$SSR_n = \frac{P_n}{C_n}$$

where (SSR_n) is the self-sufficiency ratio for nutrient (n), (P_n) is the amount produced domestically for this nutrient, and (C_n) is the corresponding population consumption (or demand) for this nutrient under the considered dietary pattern.

Domestic supply estimates were derived for 24 macro- and micronutrients, by converting agricultural production data into nutrient quantities, utilizing standardized food composition tables **(see "Agricultural Production" sub-section)**. National demand for the same set of nutrients were calculated based on two dietary scenarios: actual dietary patterns **(see "Food and Nutrients Actual Dietary Consumption" sub-section)** and the Recommended Dietary Allowances (RDAs) established as healthy dietary reference **(see "Dietary References for Food and Nutrients Healthy Recommendations" sub-section)**. This framework was used to assess the extent to which domestic food production meets population-level demand, including energy, macronutrients, and selected micronutrients. It also enabled comparison between actual nutrient intake and recommended dietary levels.

Classification of food and agricultural products into food groups

To examine the contribution of different foods to production, consumption and nutrient self-sufficiency, the detailed list of individual crop and animal products was aggregated into broader food groups following the classification of EAT-Lancet dietary reference. Within this framework, foods are organized into groups: **i)** crop-based food groups; cereals, tubers, vegetables, fruits, legumes, nuts, sugar and sugar products, and other plant products, and **ii)** animal-based food groups; beef and lamb, pork, poultry, eggs, dairy products, and fish. This harmonized food-group structure provides a consistent basis for assessing the relative contribution of each group to France's food production and consumption patterns and to the self-sufficiency levels of individual nutrients. It also enables a further comparison between actual food-group consumption and a normalized benchmark of healthy dietary intake based on the EAT-Lancet dietary reference.

Food groups self-sufficiency level and their partial contribution to each nutrient production/consumption and self-sufficiency target.

First, food group self-sufficiency ratios (SSR_f) were calculated in terms of quantity and energy under two dietary scenarios; **i)** actual consumption in France in 2014; and **ii)** the EAT-Lancet dietary recommendations. This enabled a direct comparison of actual food group intakes with those prescribed by an optimized dietary framework, thereby assessing self-sufficiency under both real-world and a healthy dietary condition.

$$SSR_f = \frac{P_f}{C_f}$$

where *(SSR_f)* is the self-sufficiency ratio for food group (f) expressed of energy (i.e., calorie) and quantity (i.e., gramme), *(P_f)* is the amount produced domestically for this food group in terms of energy and quantity, and *(C_f)* is the corresponding consumption (or demand) for this food group in terms of energy and quantity; and that under the considered dietary scenarios (i.e., actual pattern or EAT-Lancet reference).

In a further step, we applied k-means clustering to food groups self-sufficiency ratios *(SSR_f)* calculated for France under two dietary benchmarks: actual consumption patterns and EAT-Lancet. Each food group was represented by its paired *(SSR_f)* values across these two benchmarks, and they were partitioned into four clusters. The number of clusters was selected based on interpretability and stability considerations, including inspection of within-

cluster variance and centroid separation. This unsupervised approach enabled the identification of classes of food groups sharing similar self-sufficiency profiles across dietary scenarios, thereby revealing distinct patterns of structural robustness and vulnerability within the national food supply.

Second, for each food group, we quantified its relative contribution (%) to both total production and consumption of each nutrient. **Third,** to capture the nutritional dimension of each food groups, we computed partial food group self-sufficiency ratio *($PSSR_{f,n}$)* relative to each individual nutrients, defined as the partial contribution of each food group production for a nutrient, toward meeting actual consumption levels of this nutrient specific intake targets from this food groups. **For example, the *PSSR (cereals,zinc)*** is the ratio of the amount of zinc supplied by domestic cereal production with the amount of zinc actually consumed through cereal food items, thereby indicating the degree of partial self-sufficiency of cereals for zinc provision. This dual-layer approach allowed for the simultaneous evaluation of food-based contribution on nutrient status within a unified analytical framework.

$$PSSR_{f,n} = \frac{P_{f,n}}{C_{f,n}}$$

where:

- $PSSR_{f,n}$ is the partial self-sufficiency of food group f ; and its relevant contribution ratio for nutrient n production and consumption ;
- $P_{f,n}$ is the amount of nutrient n provided from domestic production of food group f;
- $C_{f,n}$ is the amount of actual consumption of nutrient n provided from the consumption of food group f.

Structure and diversity of food group contributions to nutrient self-sufficiency

Structure and diversity of food groups contribution to each nutrient intake has been conducted using a counting approach defined as the number of food groups meeting the appropriate partial self-sufficiency threshold *($PSSR_{f,n}$)* for that nutrient **(see "Food Groups Contribution Assessment" sub-section)**. This indicator was used to characterize diversity in two complementary ways. First, we quantified the proportion of food groups that achieved partial self-sufficiency levels for major nutrients, providing a measure of the breadth of nutrient supply across the diet. Second, we examined the relative proportion of crop- and animal-based food groups to this contribution to nutrient self-sufficiency, thereby capturing

the structural balance of the food system. This dual perspective allowed evaluating not only the adequacy of nutrient provision across multiple food groups but also the resilience of the production system, as reflected in its sensitivity to the share of plant and animal sources to self-sufficiency under varying dietary and production scenarios.

Regionally downscaled assessment

Regional variation in food and nutrient self-sufficiency was assessed by downscaling production and consumption data to France's twelve administrative regions. This approach enabled the evaluation of spatial heterogeneity in both food and nutrient self-sufficienct and dietary diversity. The analysis proceeded in several steps. First, we quantified the level of self-sufficiency for each nutrient in each region to identify both the number of regions achieving self-sufficiency across all nutrients and, conversely, the number of nutrients for which self-sufficiency was achieved in each region. Second, we identified regions exhibiting major nutrient self-sufficiency deficits, as well as those falling within a critical self-sufficiency range (0.95–1.05), and we assessed across regions the nutrients most frequently falling in these two categories. Third, we examined the relative contributions of plant-based and animal-based food groups to nutrient supply in each region, identifying regions where major nutrient intake was supported predominantly by one source type versus those with a balanced contribution. Finally, we assessed the potential resilience of regional food systems by analyzing the logical flow and contribution of food groups under hypothetical crisis scenarios, such as border closures, to evaluate local capacity for sustaining nutrient adequacy. This framework provided a spatially explicit perspective on the strengths, vulnerabilities, and resilience of France's regional food systems.

Authorship contribution statement

Achraf Mamassi: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing - original draft. **Marianne Cerf:** Conceptualization, Data curation, Methodology, Validation, Writing - review & editing. **Francois Mariotti:** Conceptualization, Investigation, Resources, Supervision, Validation, Writing - review & editing. **Philippe Lescoat:** Conceptualization, Investigation, Validation, Writing - review & editing. **Francesco Accatino:** Conceptualization, Formal analysis, Project administration, Resources, Supervision, Validation, Writing - review & editing.

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Competing interests’ statement

All authors declare no financial or non-financial competing interests.

Data availability

All data generated or analysed during this study are included in this published article [and its supplementary information files].

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