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Forecasting animal protein supply in Asia and Europe in light of climate change, population growth and land pressure

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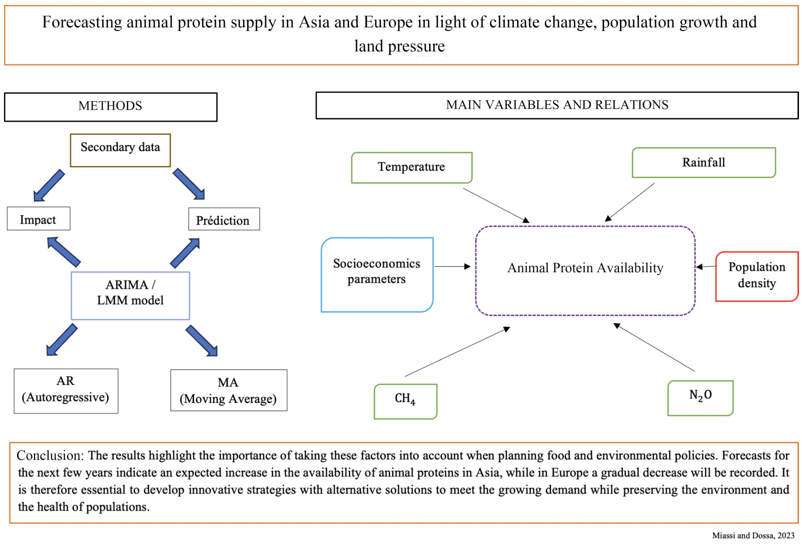
In Brief
This article examines the future availability of animal protein in Asia and Europe, considering the impacts of climate change, population expansion, and increasing land use pressures.

Graphical abstract



Highlights

- Global trends indicate a downward trajectory in average protein supply.
- Anticipated decline in per capita animal protein availability in Asia and Europe in the near future.
- Impact of climate change on the production of animal protein across Asia and Europe.
- Rising populations expected to amplify demand for animal protein.
- Land constraints pose significant risks to the sustainability of protein supplies.
- Predictive models developed from environmental, demographic, and agricultural inputs.

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Forecasting animal protein supply in Asia and Europe in light of climate change, population growth and land pressure

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Abstract

This study delves into the intricate nexus of climatic, demographic, economic, and environmental variables, collectively shaping the availability of animal protein in Europe and Asia. The study analyzes interrelationships and reveals compelling outcomes. Notably, the global phenomenon of climate change, unmistakably linked to human activities, surfaces as a pressing concern. Temperature escalation, manifesting with regional nuances, underscores the urgency of collective efforts to combat climate impact, particularly pronounced in areas like Indonesia and the Mediterranean. This underscores the imperative for immediate collaborative action to ameliorate climate consequences. Meanwhile, the surging emissions of CH_4, CO_2, and N_2O pollutants, primarily from industrial and agricultural sectors, pose a critical challenge. This mandates robust regulation within global environmental strategies and ongoing dialogues. In the realm of demography, relentless global population growth exerts formidable stress on natural resources and animal reserves. This burgeoning populace poses formidable tests for ensuring forthcoming food security and sustained animal protein availability. Economic analyses disclose variances in national gross incomes and animal protein prices, reflecting geographic distinctions. Heightened incomes signify enhanced purchasing power, while price oscillations correlate with health issues like avian flu. Multivariate analyses employing mixed linear regression models unveil the profound influence of select parameters such as temperature, pollutant emissions, population density, and production indicators on animal protein availability. This underscores the pivotal role of these factors in devising comprehensive food and environmental policies. Projections for forthcoming years anticipate augmented animal protein availability in certain Asian regions (Indonesia and Japan), though still beneath requisite demands, juxtaposed against a gradual decrement in Europe. Faced with these realities, the necessity to cultivate innovative strategies with alternative solutions comes to the fore. Exploring dairy and plant-based protein substitutes can meet rising demands while conserving the environment and public health.

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Introduction

Food is the process by which humans obtain the nutrients they need for their growth and development to ensure the proper functioning of their life cycle[1]. According to the Food and Agriculture Organization of the United Nations, a healthy diet is an essential condition for health, productivity, and well-being in general[2]. But, poor diet, according to the World Health Organization, is one of the main risk factors for a series of chronic diseases[3]. Thus, diet is a major determinant of health and should therefore not be neglected[4].

Indeed, food involves seven essential nutrients which are the main components of the meals we consume. These are carbohydrates, fats, proteins, vitamins, minerals, fiber and water. Each of these components performs specific functions within various metabolisms. Proteins provide adequate amounts of amino acids necessary for growth, development of the body, maintenance, repair, and replacement of damaged tissues, and production of metabolic and digestive enzymes. In addition, they are essential constituents of hormones[5]. Present in foods of animal and plant origin, they constitute an essential element of the human diet. According to the WHO, protein should account for up to 15% of our daily meals, which equates to a protein intake of 0.83 g/kg[6]. Furthermore, the FAO has shown that protein deficiencies, particularly of animal origin, are among the most widespread nutritional deficiencies in the world[7]. Aware of this, scientific research has increased with the aim of investigating the sources of proteins in food. Thus, science has proven that proteins are present in distinct degrees in different foods. They are found in large quantities in foods of animal origin, such as various meats, eggs, and milk and its derivatives[1]. Fardet[8] showed that, even if the impact of chewing solid foods is important, the nutritional quality of proteins of animal origin is higher than that of plant origin. Nys et al.[9] also showed for example that the egg is a perfectly balanced source of protein which contains 60% white (saline solution comprising 11% protein), 30% yolk (50% water, 16% protein, and 34% lipids). Similarly, according to Grigg[10], other animal product groups such as fish contain protein (16.8 to 17.9%). Beef (dressed carcass), lamb (dressed carcass), pork (dressed carcass), and chicken (raw, meat only) contain proteins at 15.8%, 14.6%, 13.6% and 20.5% respectively. Dairy products such as fresh milk, dried skimmed milk, cheeses, and raw whole eggs contain 3.3%, 36.4%, 22.8-35.1% and 12.3% protein respectively.

However, according to FAO statistical data, the average protein supply is increasingly declining around the world. Thus, between 2014 and 2020, the daily supply of protein per capita (in grams/capita/day) increased from 78.4 to 28.8 in Asia, from 101.5 to 59.7 in Europe, from 64.7 to 13.8 in Africa, from 83.50 to 39.90 in Central America and 83.60 to 44.80 in Latin America. These data thus confirm the results of Tilman & Clark[11] who concluded from their research that animal protein consumption models are not sustainable given the growth of the world population and food demand. This same result was observed by Aveyard et al.[12] a few years later.

All these analyses allow us to hypothesize that the reduction in the quotient supply of animal proteins is proportional to the various environmental factors such as the quantities of atmospheric pollutants emitted, the density of the population without forgetting the climatic parameters. Furthermore, it has been proven that the consumption of animal proteins induces the intensification of animal production which often generates disastrous results, due to their negative impacts on the environment as well as animal and human health[13]. Additionally, food systems actively contribute to global greenhouse gas emissions, deforestation and water consumption[14]. Additionally, anthropogenic CO_2 emissions threaten the adequacy of protein intake worldwide and increased atmospheric CO_2 may increase disparities in protein intake within the most vulnerable countries[15]. Thus, the availability of protein sources is therefore called into question on a global scale.

The present study mainly focuses on Europe and Asia and aims to analyze the current availability of animal proteins on these continents. This study also aims to predict this availability by 2030 given the mobility of climatic, environmental, and demographic factors.

Methodology

Study area

The decision to focus on Asia and Europe as the study regions is grounded in compelling reasons. A recent report by Food Innovation Australia Limited (FIAL) underscores a significant global surge in protein consumption, with a staggering 40% increase observed between 2000 and 2019. Notably, over half of this consumption surge is attributed to Asia, a continent notably renowned for its high aquatic product intake, averaging at 24.5 kg per capita in 2019. Similarly, Asia's contribution to global poultry production, including eggs, is noteworthy, accounting for around 60% of the global output. This dominance, particularly in the realms of fish and poultry proteins, positions Asia prominently on the world stage. This prominence is further underscored by 2019 data from the OECD/FAO, indicating that poultry was the globally most produced and consumed meat, with a total of 129 million tons.

In parallel, the issue of excessive consumption of animal proteins is evident in developed regions, notably Europe. Notably, European countries exhibit a protein consumption rate estimated at 150% of the recommended FAO intake benchmarks. Projections also point to a doubling of current consumption on this continent by 2030, an anticipated addition of roughly 40 million tons. This impending demand surge situates Europe as the second-largest consumer after Asia. This elevated demand for animal proteins within Europe underscores its relevance in the study.

Selection of target countries was equally strategic, reflecting the pivotal role of protein consumption within each continent. In Asia, China emerges as the largest market for animal protein, trailed by India and Japan, making them integral to the study's focus. In the European landscape, the trio of France, Germany, and Spain captures attention. Their inclusion stems from their leadership in global animal production, particularly in monogastric categories such as pigs and poultry, alongside dairy products. These countries shine as primary contributors to pig meat production within the European Union, boasting a remarkable 150 million reared pigs, far surpassing cattle numbers.

The choice of Asia and Europe, alongside the selection of specific countries, establishes a strong foundation for the study, enabling a comprehensive exploration of the complex dynamics driving animal protein consumption and availability on a global scale.

Data collected and methods of collection

This study uses data from international organizations like the FAO and the World Bank to understand the factors influencing animal protein availability in Europe and Asia. The spectrum of proteins under scrutiny in this research encompasses a broad array of sources. This encompasses meats originating from cattle, sheep, goats, pigs, and poultry, in tandem with aquatic species like fish. Furthermore, the study considers eggs and various other categories of meat, as meticulously delineated by the FAO on its official platform. These datasets encompass a multifaceted range of information spanning climatic, economic, and societal dimensions, enriching the investigative scope of the study.

Climatic factors

The influential role of climatic data in shaping the accessibility of animal proteins is multifaceted, primarily encompassing precipitation, temperature, and atmospheric pollutants. Precipitation and temperature, both marked by substantial variability, exert significant repercussions on the livestock sector. This variability, experienced on a global scale, inherently diminishes overall animal production yields, a phenomenon underscored by mounting research[16,17]. The ramifications of these climatic shifts are directly manifest in heat stress, augmented morbidity, and heightened livestock mortality. Furthermore, these effects extend indirectly, notably through the degradation of food and fodder quality and availability[15]. To capture the essence of these parameters, data spanning three decades (1990–2020) were sourced from the World Bank's repository[18]. Beyond precipitation and temperature, other climatic factors, exemplified by atmospheric pollutants, significantly influence animal production dynamics. Noteworthy contributions to this effect come from studies by Tchaker[19] and FAO[20]. Atmospheric pollutants, encompassing carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), assume pivotal roles in the greenhouse gas phenomenon. This phenomenon, directly tied to the surge in global temperatures, amplifies heat intensity[19,21,22]. The ensuing warming, exacerbated by pollutants, instigates a cascade of adverse consequences, including the extinction of plant and animal species, compounded by an escalation in climatic catastrophes such as droughts, storms, heavy rains, and cyclones[19,22]. Tropical plants tend to be more vulnerable when exposed to climate change[23]. Data encompassing a similar span of three decades (1990–2020) were procured from the website of the Food and Agriculture Organization of the United Nations (FAO) to comprehensively address each of these parameters.

Economic factors

The trajectory of animal protein consumption, alongside its discernible disparities, is intricately intertwined with an array of economic considerations. Notably, the prevailing standard of living, as characterized by the average income of a populace, stands as a pivotal economic facet shaping these patterns[24]. A pivotal inference drawn from this premise stems from the fact that low- and middle-income nations tend to exhibit per capita animal protein consumption at levels below 40% of their high-income counterparts[24]. Enhanced income levels emerge as a linchpin in determining access to animal protein sources. This is accentuated by the price dynamics governing these proteins, an influential determinant guiding their consumption trends. Consequently, animal protein sources attain a relatively higher accessibility and availability within high-income countries, a comparative advantage compared to less prosperous regions[1].

This viewpoint aligns seamlessly with the assertions made by Caillavet et al.[25], who highlight the intrinsic sensitivity of consumers to fluctuations in the price of animal products. A noteworthy repercussion of such price fluctuations is the discernible shift in consumer behavior. Specifically, a surge in prices triggers a responsive reduction in the consumption of animal protein. This inherent connection between price dynamics and consumption patterns emphasizes the overarching role of economic factors in shaping the trajectory of animal protein consumption across diverse societal strata.

Social factors

While meteorological conditions encompassing temperature, rainfall, and air pollution, in addition to economic considerations involving income and price, unquestionably hold paramount importance in shaping protein availability, it becomes imperative to underscore the pivotal influence of a burgeoning population. Research endeavors within this domain have underscored that the persistent growth of populations, notably within pivotal nations, fosters an increasingly robust demand for animal products[26]. Highlighting this aspect, Caillavet et al.[25] and esteemed bodies like[27] ascribe a pivotal role to demography within the intricate dynamics governing protein availability. In a parallel vein to air pollutants, the acquisition of economic and social data spans a comprehensive three-decade span (1990-2020), collated from the repository of the Food and Agriculture Organization of the United Nations (FAO) website.

Other factors

In addition to the array of factors mentioned earlier, this study has embraced the inclusion of supplementary parameters, notably land utilization for both agricultural cultivation and permanent as well as intermittent grazing. This is especially significant within the context of a well-established interconnection between agriculture and animal production (breeding). In this context, the term 'permanent grazing' alludes to the sustained utilization of the same natural space by livestock, while 'temporary grazing' pertains to periodic animal exploitation of spaces, allowing pastures to regenerate.

Consequently, livestock farming emerges as a pivotal catalyst for fostering sustainable agricultural development. Its remarkable capacity to temper environmental impacts on soil quality through the infusion of organic manure from animals underscores its significance[28]. Simultaneously, it's crucial to note that a substantial portion of agricultural land is utilized for producing feed for farm animals, as certified by the FAO[29].

In juxtaposition to the indicators utilized for gauging animal protein availability, this study has harnessed data concerning total production (in tons), stock changes (in tons), and individual daily protein availability (in g/person/day). These data points, spanning the available timeframe on the FAO platform (2010−2020), have been meticulously evaluated within the ambit of the present study. This analysis aims to determine the impact of supplementary factors on animal protein availability and consumption patterns.

Method of analysis

Chronological evolution of the different parameters

The examination of the chronological progression of the distinct study variables was conducted through the application of time series analysis methods. These methods hold the dual capability of initially retracing the trajectory of variables over time and subsequently facilitating the description and explication of a variable's evolution across temporal dimensions. Moreover, these methods offer the potential for predicting future trajectories, upon which development policies and strategies can be anchored[30].

Determinants of animal protein availability

For the investigation into the factors influencing protein availability at an individual level across various countries, the study employed the Linear Mixed Model (LMM).

Linear Mixed Models (LMMs), renowned for their robustness and adaptability, serve as a potent analytical tool for dissecting grouped data, notably longitudinal or repeated measures across observation units[31]. This aligns seamlessly with the current study's context, encompassing data spanning multiple decades (1990−2020) within each of the six countries. A distinctive attribute of LMMs resides in their capacity to accommodate a dual-layered data analysis approach: a universal (finite) level shared by all observation units through 'fixed' effects, and a distinctive (infinite) level manifested through 'random' effects. Fixed effects parameters are uniform across all explanatory variables (including climate, economic and social parameters, as well as animal protein production indicators like total protein quantity and stock levels). In contrast, random effects introduce variability specific to each observation unit (in this case, individual countries). This incorporation of random effects within modeling serves as an effective mechanism for exploring data variability and discerning diverse sources of variation including those attributed to random effects and error[31].

Within the context of this study involving six countries equitably distributed between Europe and Asia (Germany, France, Spain, China, Japan, and Indonesia), it becomes imperative to accentuate the role of the 'country' variable as a random factor. This strategic approach gains significance owing to the notable economic disparities inherent among these nations. Such an approach affords a nuanced examination of how these diversities inherently impact research outcomes. The European countries considered in this study are recognized as developed nations, boasting elevated economic status, particularly in terms of income, and serving as significant importers of animal proteins[25]. Additionally, discernible disparities in environmental conditions exist across this cohort[32]. Consequently, designating the 'country' variable as random, thereby accentuating its influence, holds relevance in elucidating the intricate interplay between economic and environmental factors within the research paradigm.

Synthetic writing of an LMM with K random effects is of the form[31]:

$$y = X\beta + Zu + e \quad (1)$$

With

• y, the response random vector of size N;

• β, the vector of the unknown parameters of the fixed effects, of size p, and X its assumed known incidence matrix and of dimension (N × p) ;

• u, the vector of the set of random effects, decomposed by the K of random effects ;

• Z, the known incidence matrix associated with the random effects.

In this case, the general equation of the LMM model used is as follows:

$$y = \beta_0 + \beta_1 \times Rainfall + \beta_2 \times Temperature + \beta_3 \times CH_4 + \beta_4 \times N_2O + \beta_5 \times Income + \beta_6 \times Price + \beta_7 \times Farming_{lands} + \beta_8 \times Population + \beta_9 \times Total_{production_{protein}} + \beta_{10} \times Stock_{variation} + u_1 \times Country + e \quad (2)$$

Where y is the amount of protein available to an individual per day in each country.

To perform the forecasts, the ARIMA approach was used, in the sense that it is considered one of the best approaches to obtain the best performance in terms of prediction when it comes to time series data[30].

Consider the ARIMA (AutoRegressive Integrated Moving Average) time series of an explanatory variable $Y_t X_t$ written in the form of a linear transfer function of a series of noises:

$$Y_t = \sum_{j=0}^{\infty} \varphi_j \epsilon_{t-j} \quad (3)$$

To obtain a forecast Y_{t+L} (L denoting a next year or time lag) of the explanatory variable X, the following equation was used[30]:

$$Y_{t+L} = \sum_{j=0}^{\infty} \varphi_j \epsilon_{t+L-j} \quad (4)$$

In the present scenario, the primary explanatory variables employed predominantly encompass those exhibiting noteworthy effects within the conducted LMM model (Table 1). These prognostications have been projected onward to the year 2030. It's pivotal to underscore that the selection of this year emanates from the premise that these projections derive from the sway of explanatory variables, which themselves have undergone prognostication. Consequently, extending this timeframe could potentially introduce vulnerabilities to the reliability of the envisaged outcomes pertinent to the variable of interest. These diverse analyses were conducted utilizing R version 4.3.0 software, while Excel was harnessed for the input of data acquired from the two information sources, namely World Bank and FAO.

Results

Chronological evolution of the main parameters

Chronological evolution of rainfall

Our analysis shows similar fluctuations in rainfall patterns across three European nations (France, Germany, Spain) from 1990 to 2020. However, despite the irregular and akin oscillations across these countries, distinct general trends manifest between the European counterparts.

The average annual rainfall in France increased slightly from 866 mm in 1990 to 928 mm in 2020, while Germany remained relatively stable at 848 mm in 1990 to 824 mm in 2020. Spain saw a marginal increase from 571 mm in 1990 to 684 mm in 2020. While the trends vary among the European countries studied, France consistently had the highest average annual rainfall, followed by Germany, and Spain with the lowest. This spatial-temporal variation aligns with findings from the European Environment Agency (EEA), which notes a 70 mm per decade increase in precipitation within North-Western European nations, including French territory. EEA further underscores the tendency towards wetter conditions in Northern Europe during the 20th century, contrasting with southern parts of the continent, including Spain, where a progressive decline in precipitation is observed[34]. Additionally, Germany's precipitation stability finds support in prior research; E-OBS data corroborates the absence of significant changes in average annual European precipitation since 1960[34,35].

Turning to Asian countries, a comparable spatial variation comes to light, wherein Indonesia and Japan observe upward trends in rainfall while China experiences a gradual decline. Indonesia witnesses significantly greater rainfall compared to the other two nations, with a substantial change from 2,914 mm (1990) to 3,594 mm (2020). Japan also experiences a slight

Table 1. Summary of the parameters used for the LMM model.

Variables	Description	Sources	Expected effects	Reference
Dependent variable				
Protein available	Amount of protein accessible or available to an individual per day (g/person/day)	**CAM**		**Variable of interest**
Independent variables				
Rainfall	Annual rainfall (mm)	World Bank	+	[16, 17]
Temperature	Mean annual temperature (°C)	World Bank	–	[16, 33]
CH_4	The amount of methane (kiloton) in the atmosphere	FAO	–	[19, 20, 22]
N_2O	The amount of nitrous oxide (kiloton) in the atmosphere	FAO	–	[19, 20, 22]
Income	Gross annual income per capita (USD)	FAO	+	[1, 24]
Price	Annual average price of a ton of animal protein (USD/ton)	FAO	–	[1, 25]
Farming_lands	Total area of agricultural land (hectares)	FAO	+	[28, 29]
Population	Total population density	FAO	–	[25, 27]
Totalproductionprotein	Total annual amount of protein produced nationally (tons)	FAO	+	Considered just as an additional indicator of availability
Stock_variation	Amount of stored protein available after consumptions and sales	FAO	+	Considered just as an additional indicator of availability
Country	The six countries considered	–	Random	Not quantifiable

increase, recording an ascent of approximately 100 mm (1,810 mm in 1990 to 1,918 mm in 2020). In contrast, China, with the lowest recorded rainfall among the Asian countries considered, observes a modest decrease from 903 mm (1990) to 832 mm (2020). These outcomes parallel those in European nations, particularly the spatial variability of precipitation amounts over the past three decades. This variability is underscored by the United Nations (UN), which classifies the Southeast Asian region as the most climate-change-vulnerable in Asia. This characterization emphasizes the region's susceptibility to sea-level rise, underscoring the consequential impact of heavy rainfall on communities residing at lower altitudes[32].

Chronological evolution of the temperature

In contrast to rainfall patterns, temperature consistently shows an upward trajectory, regardless of geographical location.This outcome substantiates the findings of numerous studies that highlight enduring shifts in temperature patterns, emblematic of global warming characterized by a substantial rise in this parameter over time. These shifts have been attributed to human activities, as underscored by Meseguer-Ruiz & Olcina Cantos[36] over past decades. These escalations align with the context of global warming on a global scale[37].

However, the average annual values of temperature also show spatial divergence similar to rainfall patterns. Notably, the Indonesian region registers the highest temperatures, ranging from approximately 25 °C (1990) to around 26 °C (2020). This observation reiterates the classification outlined by the UN[32], situating Indonesia within the group of countries most susceptible to climate change. This vulnerability is manifested in Indonesia through phenomena like rising sea levels coupled with severe global warming. Conversely, in Europe, Spain exhibits the warmest climate, with temperatures hovering around 15 °C (2020). This phenomenon is attributed to Spain's location within the Mediterranean region, a fact corroborated by the Intergovernmental Panel of Experts (IPCC) . This conclusion finds reinforcement from recent studies that highlight the distinctive nature of the Mediterranean area in terms of temperature trends and the overarching global increase. These studies acknowledge the Mediterranean's unique characteristics within the broader climatic context[36,38]

Chronological evolution of atmospheric pollutants

Analyzing air pollutant emissions is crucial in understanding the climate change impact on a specific parameter. Such an endeavor enables a deeper comprehension of the influence of distinct climatic factors (including rainfall, temperature, and pollutants) on the specified parameter. In this study's context, the parameter under scrutiny pertains to the availability of animal proteins.

Hence, an examination of pollutant concentrations across the target countries serves to illuminate emerging trends for each pollutant. This analysis also furnishes an initial insight into the pollutant that holds the potential to exert a substantial impact on the availability of animal proteins in each country. Methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O) constitute the primary pollutants under consideration. In Europe, emissions of this pollutant are relatively low, accompanied by a descending trajectory over time particularly evident in France (3,485 kilotons in 1990 to 2,847 kilotons in 2020) and Germany (6,045 kilotons in 1990 to 2,525 kilotons in 2020). The considerable reduction in methane emissions quantities across the European continent can be attributed to the strategic measures implemented by the European Union (EU). This strategy revolves around curtailing the importation of natural gas throughout the continent. Notably, the EU underscores that methane emissions linked to imported gases and liquefied natural gas (LNG) range from three to eight times higher than emissions occurring within the EU[39,40]. Furthermore, emissions of methane primarily stemming from agricultural practices significantly surpass those from fossil fuel production and utilization[32]. However, the latter sources of production are deemed more manageable and cost-effective to mitigate, thus warranting substantial reduction efforts[39]. The implementation of this strategy, reinforced by initiatives like the 'Oil and Gas Methane Partnership', the zero pollution action plan of 2021, and the 'Clean Air Outlook' program of 2022, has played a pivotal role in diminishing EU domestic natural gas production[39,41]. In contrast, the temporal analysis of methane emissions quantities in Asian countries (excluding Japan) reveals a marked upward trajectory in Indonesia (11,551 kilotons in 1990 to 16,887 kilotons in 2020) and particularly in China (42,010 kilotons in 1990 to 68,969 kilotons in 2020). This observation aligns with findings from other studies that pinpoint China as experiencing substantial growth in fossil fuel emissions[39,42]. The surge in emissions of this pollutant in Asian countries, especially China, is underpinned by multiple factors. In addition to being a significant natural gas exporter, China stands as the globe's largest producer and consumer of rice[43], contributing 28% to global rice production according to the Food and Agriculture Organization of the United Nations[43]. Rice cultivation, well recognized as a major source of agricultural methane emissions[32], is linked to China's emissions growth.

The trajectory of methane (CH_4) evolution in diverse countries could yield substantial implications for animal protein availability, particularly prominent in Asia and specifically in China. The increase in CH_4 emissions could potentially pose challenges to animal protein availability, precipitating an elevation in livestock mortality rates[16].

The temporal trajectory of carbon emissions within the study period mirrors the patterns observed for methane emissions. In fact, CO_2 emissions in the European context exhibit a gradual decline, with the exception of Spain a nation still witnessing an upward trend. Spain's CO_2 emissions show annual quantities approaching those of France, registering at 226,340 kilotons and 288,357 kilotons in 2020, respectively. This unique aspect within the Spanish territory aligns with the Mediterranean climate's distinct characteristics, rendering it more susceptible to climate change impacts[36].

Mirroring the trends seen in methane emissions, Asian countries experience a notable surge in CO_2 emissions. This escalation is attributed to the burgeoning industrial sector in Asia[44]. The establishment of multiple industries engenders substantial energy demand largely met by oil and gas sources[44]. However, the oil and gas industries rank among the primary global contributors to greenhouse gas emissions, releasing significant amounts of hazardous air pollutants, including carbon dioxide[45]. This observation aligns with multiple Asian studies, revealing that the utilization of natural gas in industrial operations has resulted in heightened atmospheric CO_2 levels[44]. Consequently, the rise in atmospheric carbon dioxide concentrations correlates positively with gas and energy consumption[45]. This elucidates the elevated presence of these pollutants in Asian countries, where industrialization is progressing at a rapid pace[44]. Consequently, akin to the impact of methane, the progression of CO_2 emissions carries tangible ramifications for animal protein availability. This effect is particularly pronounced in Asia, where its continuous increase over the years corresponds with amplified livestock mortality rates[19].

The evolution of nitrous oxide (N_2O) over time corroborates the patterns observed in the case of the preceding two pollutants (CH_4 and CO_2). The N_2O concentration within the European environment displays a progressive decline across the three European countries. In both France and Germany, the quantity of this pollutant has transitioned from over 220 kilotons (1990) to approximately 140 kilotons (2020), while in Spain, it was 87 kilotons in 1990 to less than 85 kilotons in 2020. Conversely, Asian countries, particularly Indonesia and China, have continued to experience escalating emissions of this pollutant into their environment until 2020. These findings can be attributed to similar drivers as observed for the two prior pollutants. Asian nations persist as key exporters of natural gas while concurrently emerging as potential consumers of energy sourced from these gases for industrial applications. These energy sources often entail substantial emissions of hazardous pollutants such as nitrous oxide[44].

Collectively, these results underscore spatial and intercontinental variations in several climatic parameters encompassing rainfall, temperature, and the quantities of atmospheric pollutants (CH_4, CO_2, and N_2O). The findings notably highlight more pronounced challenges within Asian regions as compared to European nations. This divergence could potentially engender significant hurdles concerning the availability of animal proteins, particularly impacting regions grappling with exacerbated climatic conditions and heightened pollutant emissions. The study also delved into social factors including population density, specific economic facets related to animal protein (prices and incomes), agricultural production indicators (agricultural area versus grazing land), and indicators of animal product protein availability (total production quantity, stock fluctuations, and individual availability within each country).

Total population

There is a general trend of population density increase in all these countries, except for Japan which experienced a significant decline in its population between 2010 and 2020. However, overarching patterns indicate a rising trajectory in the populations of the various countries under consideration. This demographic surge in these diverse countries is primarily attributed to substantial population growth within major urban centers. According to Cheshire & Magrini[46], the climate of large cities has emerged as a decisive factor contributing to the notable population escalation observed over the last two decades. Nonetheless, other factors, including natural growth rates in areas outside major urban centers, should not be disregarded[46].

The global demographic explosion is by no means a novel topic, as between 1900 and 2000, the global population experienced a remarkable surge, escalating from 1.6 to 6 billion inhabitants[47]. This situation prompted Western nations, particularly within the European Union, to embark on initiatives targeting declining birth rates through comprehensive family planning strategies aimed at managing issues related to hunger and poverty[47]. Over the years, some critics have attributed the persistence of population growth to perceived shortcomings of family planning policies, asserting that these policies fail to effectively account for the individuals they intend to address[47].

Furthermore, while the challenge of population explosion is discussed, several countries, both in Europe (Germany, France, Spain) and Asia (China and Japan), are grappling with declining birth rates, underscoring that the demographic growth is predominantly driven by aging populations[48]. Data from the National Institute of Statistics and Economic Studies reveals a decrease in the total fertility rate, reaching 1.83 children per woman in France and 1.50 children per woman across the entire European Union. The situation is particularly concerning in Asia, particularly in Japan, where the phenomenon of population aging is pronounced, with 28% of the population aged 65 and above, three times the global average[49]. This decline in Japan's population can largely be attributed to its aging demographic, as lower birth rates and diminished population growth often coincide with older age demographics[49]. The situation has prompted discussions in some quarters of French politics, advocating for state aid of around 900 euros upon the birth of a woman's first child[48]. In light of these findings, one can anticipate a gradual reduction in available animal proteins due to the substantial population growth witnessed in the countries under study[25,2,27].

Chronological evolution of the total agricultural and pasture area

The impact of population growth, as highlighted earlier, extends to resource management, particularly in terms of land utilization and associated resource consumption[50]. In France, a declining trend in agricultural production, dwindling from 30.5 million hectares in 1990 to 28.5 million hectares in 2020 has been observed. In Germany, this area has expanded from 18 million hectares in 1990 to 16.5 million hectares in 2020, and in Spain, it has decreased from 30.4 million hectares to 26.14 million hectares. Despite population growth, one might have anticipated an increase in agricultural land to accommodate the escalating food demand due to the surging population[51]. This logical anticipation, however, is not confirmed, primarily due to the emphasis placed by the authors on rural areas as the predominant factor in the expansion of agricultural land[50]. Nonetheless, European countries are predominantly characterized by high rates of urbanization, estimated at 72% of the EU population, driven by a dual phenomenon of rural exodus and suburbanization[52]. This migration from rural to urban areas and from central cities to suburbs has led to a progressive reduction in available agricultural land in these nations.

Conversely, in Asia, the analysis indicates a trend of increasing agricultural areas, particularly pronounced in Indonesia and China. This can be attributed to the agricultural focus of these countries, notably China, renowned as the world's leading rice producer with a 28% contribution to global production according to FAO data[43]. On the contrary, Japan displays a gradual decrease in its agricultural land area, a trend linked to its aging population, as elucidated earlier.

Regarding permanent and temporary pasture areas, a gradual and consistent growth is observed across various countries. The results obtained vividly illustrate the adoption of urban grazing, an approach advocating the maintenance of green spaces without the use of pesticides, signaling a strong inclination to reintegrate 'nature' into urban settings[53]. This trend often aligns with the concepts of urban pastoralism or urban herders[51]. However, despite this growing preference for urban grazing, agricultural land still prevails over land dedicated to livestock farming, even though agricultural areas are on a gradual decline.

In the face of shrinking agricultural land, these countries are potentially more exposed to concerns regarding animal nutrition, particularly given that products from these lands play a crucial role in livestock feeding[29]. Nonetheless, this potential food insecurity for livestock can potentially be mitigated by expanding national pasturelands, thus providing a means to counterbalance this deficiency through grazing practices. This perspective opens up the possibility that an increase in grazing areas could lead to a rise in the availability of animal proteins.

Chronological evolution of economic indicators

Previous research has solidified the understanding that access to animal proteins is more prevalent in high-income countries, driven by the pivotal influence of protein prices on consumption decisions[24]. The pricing factor remains a critical determinant in assessing animal protein intake[1]. Hence, comprehending the co-evolution of income and prices assumes paramount significance within this study, as this analysis sheds light on the ramifications of variations in animal protein availability across the six countries.

Analysis unveils a dynamic growth in this economic metric, a determinant parameter in accessibility to animal proteins as underscored by Luo & Yu[54]. In France, the average annual per capita income surged from approximately 22,500 USD in 1990 to 41,563 USD in 2020, nearly doubling their purchasing power over three decades. A similar trend is discerned in Germany (22,500 USD in 1990 to 48,000 USD in 2020) and Spain (13,600 USD in 1990 to over 27,000 USD in 2020). These incomes consistently surpass the European average of approximately 18,963 USD per capita[55]. This augmented purchasing power manifests universally and is primarily linked to escalated healthcare costs in recent years marked by the emergence of pandemics[56,57].

In the Asian context, although only Japan's purchasing power matches that of France, Germany, and Spain, an ascending trend is evident in average gross income per capita in both Indonesia and China. From 694 USD in 1990, Indonesia's average annual gross income reached 3,700 USD in 2020; while China crossed the 10,000 USD threshold in 2020, a substantial leap from the mere 400 USD per capita three decades earlier (1990). These incremental increments in purchasing power across Asia are attributed to investments directed towards these nations, which notably constitute the primary beneficiaries of foreign direct investment (FDI) inflows, accounting for over half of all FDI as reported by the United Nations Conference on Trade and Development[58].

The progressive rise in incomes during the observation period was consistently accompanied by an increase in the prices of animal protein. Thus, the cost of a metric ton of animal protein exhibited continuous growth across the various countries from 1990 to 2020, except for Spain which experienced a downward trend despite its increasing purchasing power.

Specifically, this analysis focuses on the average price of a metric ton of proteins derived from chicken eggs, fresh or chilled meat (including various livestock such as sheep, cattle, ducks, goats, horses, turkeys, leporids, geese, chickens, donkeys, mules, game, and suidae like pork). In France, the average annual price per ton of these proteins escalated from 2,600 USD in 1990 to over 3,500 USD in 2020, marking a growth of more than 34% over three decades. Germany exhibited a more pronounced increase, with the average annual price ascending from 2,000 USD per ton in 1990 to 3,300 USD in 2020, equating to a rate of approximately 65%. Despite a decrease in Spain (from 2,500 USD in 1990 to 2,000 USD in 2020), this decline might be attributed to an increasing shift towards vegetarian diets within the country. The surge in vegan food popularity, confirmed by Vegconomist[59], indicates a 34% rise in Spain's meat-free diet followers from 2017 to 2021. This dietary choice potentially decreases the demand for such proteins, especially since fish consumption is excluded from this mode[60]. However, FAO[28] attributes the escalating poultry prices to rising import demand from East Asia, exacerbated by supply disruptions due to widespread avian influenza outbreaks. Conversely, pork price increases result from inadequate supply in key producing regions, particularly within the European Union[28]. The persistence of African swine fever further exacerbates this situation, impacting local production[27].

In Asia, particularly in China and Japan, the price escalation for these proteins is significant. Over the years, the annual average price of a metric ton of animal protein surged remarkably, climbing from under 1,000 USD in 1990 to over 5,000 USD in 2020. This trend is also evident in Japan, where prices surged from 1,800 USD in 1990 to over 5,600 USD in 2020. Similarly, Indonesia witnessed an increase from 985 USD in 1990 to more than 3,900 USD in 2017. These overall price hikes in Asia are closely tied to strong demand for certain meats, particularly pork, which is a primary consumption choice across the continent. Furthermore, its availability is hindered by escalating export supplies from Brazil, the European Union, and the United States[27].

Evolution of protein availability indicators

The preceding discussions regarding the fluctuations in animal protein prices predominantly revolve around the interplay of demand and inadequate supply in the target countries. Addressing this deficit in animal protein supply becomes imperative, necessitating a synchronization of total animal protein production with the rate of population growth to meet the expanding demand. Across all countries, a trend of increasing production and stock of animal protein is evident, barring France where a gradual decline in annual animal protein quantity is observed. From 8.1 million tons in 2010, France's production has dwindled to 7.8 million tons in 2020, reflecting a 4% reduction. Association Française de Zootechnie[61] also noted this decline, attributing it to heightened awareness of the health impacts of dietary choices. Contributing factors include the environmental consequences of livestock farming, animal welfare concerns, and demographic shifts marked by an aging populace and urban lifestyles.

Conversely, other countries have witnessed a progressive surge in the production of animal-derived proteins, particularly notable in Spain where production escalated from 8 million tons in 2010 to 10.4 million tons in 2020. In China, production remains notably high, growing from 168 million tons in 2010 to 182 million tons in 2020. Nonetheless, OECD/FAO[27] observations highlight that this upswing is primarily driven by increased poultry and sheep meat production, offsetting declines in pig and beef production due to the ongoing African swine fever outbreak, which has particularly impacted China. This general increase in total production underscores the swift adaptability of production levels to global demand[27].

The correlation between the rise in total production levels and the actual availability and accessibility of animal proteins at an individual level is not straightforward. The dynamics unveil a nuanced narrative; despite an increase in population density and a decline in production, the availability of animal protein per person has shown a gradual reduction in France. Starting at 47 grams per person per day in 1990, this availability plummeted to around 42 grams per person per day in 2020. A similar trend echoes in Germany, where the availability dropped from 37 grams in 1990 to 35 grams per person per day in 2020. Contrarily, Spain experienced a noticeable surge in protein availability, escalating from less than 53 grams per person per day in 1990 to 54 grams per person per day in 2020.

Across Asia, a collective upward trajectory characterizes protein availability per individual in the three countries under consideration. Indonesia's animal protein availability per person daily escalated from 14 grams in 1990 to 25.21 grams in 2020. China experienced an increase surpassing 4 grams in 2020 compared to 1990, while Japan exhibited a more modest growth, adding about 1 gram per individual in 2020 vs 1990.

It's noteworthy, however, that the protein availability in these Asian nations still lags behind that of their European counterparts. This discrepancy can be tied to the evident variance in gross national income per capita, with the European nations displaying higher income levels than their Asian counterparts. This income-based incongruity is reinforced by FAO[24] data, which underscores that low- and middle-income countries witness a 40% lower per capita consumption of animal protein compared to high-income countries.

Delving into the pace of availability, indicative of the swiftness with which animal protein quantities become attainable to an individual, discloses an unfavorable trajectory over the last three decades, particularly in European countries and Japan. These findings intimate that over time, the rate of access to animal proteins is progressively dwindling. This suggests that the supply of these proteins in Europe and Japan continues to fall short of the mounting demand from their steadily growing populations[28]. This reality of protein demand plateauing has sparked the proposal of reshaping dietary habits towards protein-rich alternatives a proposition bolstered by the National Nutrition-Health Plan[62]. In congruence, France's Ministry of the Environment has set a target of reducing meat consumption by 10% by 2030[61], aligning with the environmental perspective.

In the context of China, the pace of evolution remains relatively stable, in line with a protein availability that advances at a similar rate as population density. This could be partially attributed to the longstanding one-child-per-woman policy, as established and enforced by the government for several years[49].

Factors determining the availability of animal protein

Table 2 presents the outcomes derived from the analysis of the fixed and random effects (country-wise) using linear mixed effects models (LMM). An examination of the results from this table reveals that approximately 72.7% of the fluctuations in protein availability at an individual level across diverse countries can be attributed to the fixed variables considered within the model. Similar results were found in recent studies in Africa[63,64].

Intriguingly, the quantity of animal protein (measured in grams) accessible to individuals in these various countries is notably influenced by factors such as temperature, methane (CH_4), nitrous oxide (N_2O), the average annual price per ton of protein, the extent of cultivated agricultural land, population density, and indicators related to animal protein production (total protein quantity produced and stock changes). The table demonstrates that an escalation in temperature, N_2O levels, population, and stock correlates with a reduction in the quantity of protein available per person across the different countries. In simpler terms, unfavorable environmental conditions involving elevated temperatures and pollutants like N_2O substantially diminish the grams of protein accessible to each individual. This aligns with Diallo et al.[16] whose findings underscore the repercussions of these climatic factors, particularly temperature, leading to heat stress that amplifies animal morbidity and mortality. This situation predominantly results from compromised food and fodder quality and availability, consequently impacting animal yields and subsequently restricting individual accessibility[33]. In a similar vein, other researchers propose that global warming, driven by pollutants including N_2O, accelerates species extinction and exacerbates climatic disasters like droughts, storms, heavy rainfall, and cyclones[19]. As plant species remain fundamental food sources for animal species, these effects are intertwined.

The adverse sign associated with the 'stock of animal protein' variable within the model's results signifies a decline in animal protein availability when the protein stock increases. This could stem from escalated imports or decreased domestic consumption due to soaring prices that surpass the purchasing capability of populations[25].

However, in contrast to these parameters, the model reveals a substantially positive impact of methane (CH_4), the average annual price per ton of protein, the area of agricultural land, and the total protein quantity produced at a national scale on the quantity of animal protein (in grams) available per individual. This contrasts Tchaker's assertions[19], which linked

Table 2. Regression coefficient of the fitting covariates of the linear mixed-effects model.

	Estimate	Std. error	t value	*p*-value
Fixed effects				
Intercept	5.231e+01	5.658e+00	9.246	1.05e-06 ***
Rainfall	1.777e-03	9.522e-04	1.866	0.067505
Temperature	−6.340e-01	2.177e-01	−2.913	0.005329 **
CH_4	7.522e-04	1.784e-04	4.215	9.38e-05 ***
N_2O	−6.667e-02	1.636e-02	−4.076	0.000154 ***
Income	5.259e-05	4.345e-05	1.210	0.231508
Price	1.087e-03	2.895e-04	3.755	0.000429 ***
Farming_lands	4.988e-07	5.720e-08	8.721	6.03e-12 ***
Population	−2.904e-07	2.523e-08	−11.509	4.72e-16 ***
Total_protein_ production	1.144e-06	8.374e-08	13,660	<2nd-16 ***
Stock_change	−1.019e-06	1.443e-07	−7.062	3.21e-09 ***
Marginal R^2 (R^2m)	0.727			
Random effects				
Groups	**Variance**	**Std.Dev**		
Country (Intercept)	63.7965	7.9873		
Residual	0.671	0.819		

Significance levels: '***' 0.001; '**' 0.01; '*' 0.05 ' increased levels of pollutants such as CH_4 to global warming and species depletion (both animal and plant). Nonetheless, this result is justified by the fact that augmented production volumes of animal protein sources lead to heightened CH_4 emissions into the atmosphere. Chouinard[65] elucidates those elements like manure and excrement from farm animals, both monogastric and polygastric, significantly amplify CH_4 emissions. Additionally, Palangi & Lackner[66] highlight that CH_4 emission also arises from enteric fermentation in ruminant animals like cattle. During the digestion process, microorganisms in the rumen, referred to as methanogens, break down plant materials into simpler components, releasing methane (CH_4) as a byproduct[26]. This, in turn, impacts animal production, creating a self-perpetuating loop.

However, the affirmative influence of price on protein availability is predominantly associated with the purchasing power of residents. Overconsumption of proteins is a distinct feature of developed countries, particularly evident in European nations where consumption hovers around 150% of recommended intakes, as per FAO evaluations[67]. This protein overconsumption is primarily attributed to income levels; developed countries with higher incomes exhibit per capita consumption of animal proteins over 40% greater than that in low- and middle-income nations[24].

The positive effect of agricultural land area is explained by the fact that products stemming from agricultural production significantly contribute to animal sustenance, both in the wild and in breeding. This aligns with FAO's emphasis that 70% of agricultural land is specifically dedicated to cultivating food for farm animals, especially fodder crops like corn, oats, and soy used primarily in livestock feed[29]. This, however, also leads to conflicts between farmers and breeders worldwide, arising from animals like cattle encroaching on agricultural plots and wildlife in natural habitats[68].

Livestock farming is perceived as a critical driver of sustainable agricultural development, primarily due to its potential to counteract soil-related environmental impacts through the supply of organic animal manure[28]. It's imperative to introduce innovative and sustainable systems to facilitate collaboration between breeders and agro-breeders, fostering increased production on both fronts[29].

Ultimately, the affirmative impact of enhanced overall production on individual availability is coherent, as increased production augments supply, which in turn satisfies burgeoning population demands. Hence, ensuring alignment between meat supply and demand at distribution points becomes imperative[69].

These effects collectively elucidate the diversity observed in protein availability among individuals across different countries. However, the model also underscores a random effect associated with the 'country' variable, wielding substantial influence on protein availability within populations. This randomness mirrors each country's unique attributes in terms of production, demand, food policies, and other local factors that contribute to shaping protein availability within societies. Among these local elements, variations in inhabitants' purchasing power play a pivotal role in protein consumption, a notion well supported by existing literature[24,25].

Prediction

The provided text discusses annual forecasts for 2030 regarding the availability of animal protein per capita in different countries. These forecasts were made considering various parameters such as temperature, CH_4, N_2O, protein prices, agricultural areas, population density, total protein production, and stock variation. The forecasts were generated using the ARIMA approach, known for its strong predictive performance with time series data (Fig. 1).

In Europe, the analysis of forecasted results indicates a declining trend in available animal protein per capita over the next decade (by 2030) across three countries. Specifically, France's animal protein availability is expected to gradually reduce to 35 g/person/day by 2030, compared to around 27 g/person/day in Germany and approximately 47 g/person/day in Spain. In contrast, the average animal protein available per person per day in 2020 stood at 42.66 g in France, 35.42 g in Germany, and 53.08 g in Spain. When compared to the required protein quantities determined based on average weight and the recommended minimum protein intake of 0.8 g/kg, it becomes evident that individuals in these European countries won't meet their protein needs, especially considering people with higher body weights.

Shifting the focus to Asia, particularly China, the forecasts also indicate a decreasing trend in accessible animal protein per individual over time. The model predicts a drop to less than 35 g/person/day in China, down from 37.98 g in 2020. However, the minimum protein requirements for Chinese men and women are estimated at 58.8 and 49.76 g/day, respectively. This projection suggests a continuous decline in availability over the next decade, possibly leading to the consumption of less common animal protein sources in these countries, similar to observed dietary shifts in China in recent years. Conversely, Indonesia and Japan are expected to experience an increase in available protein per person. From receiving less than 15 g/day of animal protein in 2010, each Indonesian is projected to have access to up to 23 g/day by 2030. Similarly, Japan's availability is set to rise from 41 to around 47 g/day. However, even with these increases, neither Indonesia nor Japan will meet their minimum protein requirements based on their respective thresholds.

The collective outcomes from various countries reveal that relying solely on animal-derived proteins won't suffice to meet minimum daily requirements or growing demands. Historically, the consumption of animal protein has steadily increased over the years. According to OECD and FAO data, between 2018 and 2020, the global average animal protein consumption was 34.1 kilograms per capita.

However, looking ahead, the model predicts a 14% rise in global animal protein consumption by 2030 compared to the 2018–2020 average. This projection is a clear indication of the growing appetite for animal-based proteins worldwide. It underscores the challenge of ensuring an adequate supply of animal proteins to meet the nutritional needs of a growing global population and highlights the need for sustainable practices in livestock production to address this demand.In light of these escalating protein needs, there's a call to rethink dietary habits and consider alternative protein sources. The National Nutrition and Health Program (PNNS) now advocates for two to three daily servings of dairy products and the promotion of leguminous plant protein sources, with a recommended minimum of two servings per week (equivalent to 200 g). This shift in dietary patterns aims to address the impending challenges posed by the rising demand for animal protein.

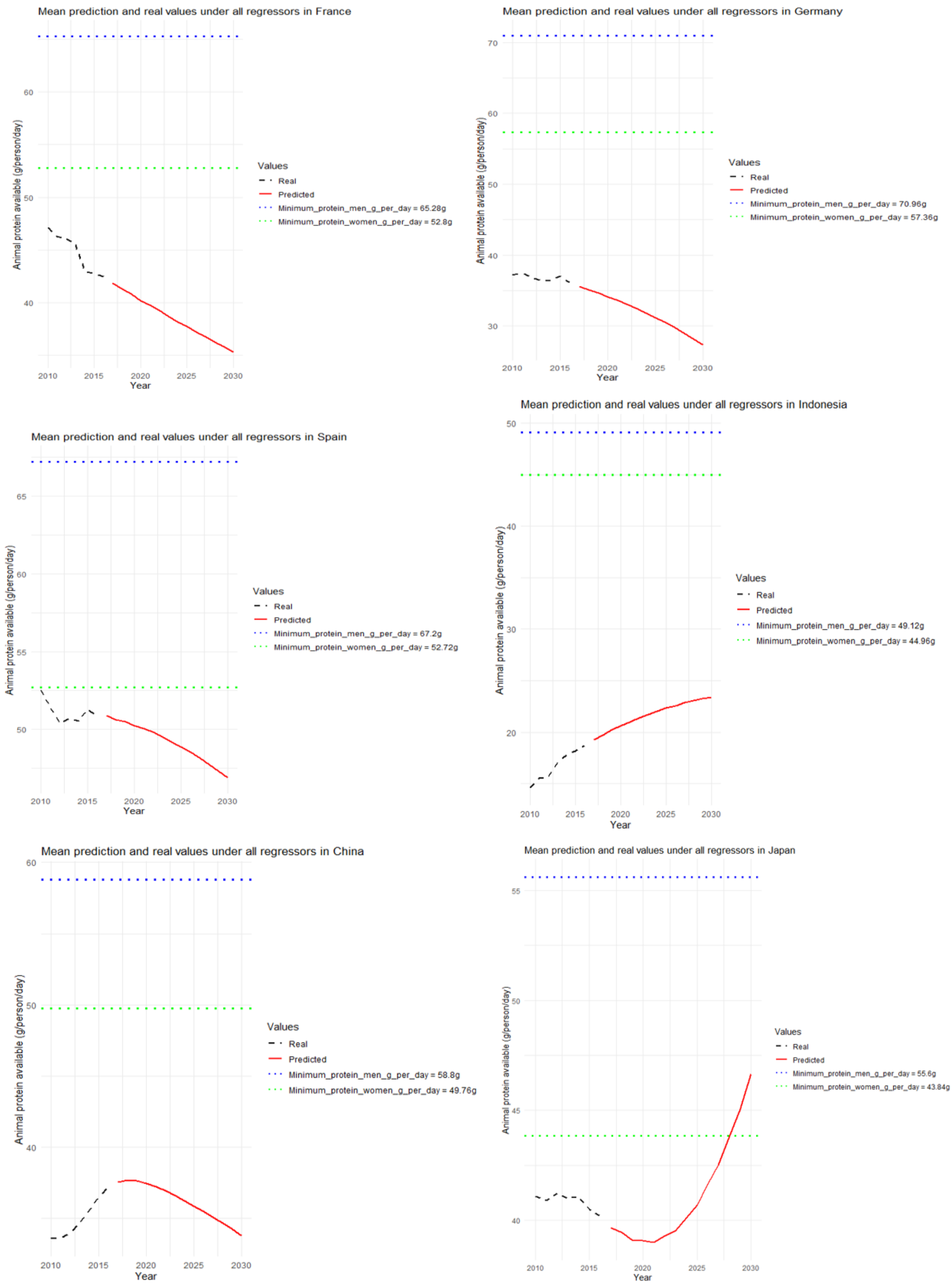

Fig. 1 Annual forecasts to 2030 of the quantity of animal protein available.

The importance of such dietary recommendations lies in addressing both the nutritional needs of the population and the broader societal and environmental concerns associated with excessive animal protein consumption. By diversifying protein sources to include more plant-based options, countries can reduce the environmental impact of agriculture, promote sustainability, and potentially improve public health outcomes by encouraging a more balanced and varied diet.

Discussion

Upon concluding the diverse analyses, it becomes evident that global warming is an overarching phenomenon primarily characterized by a substantial temperature increase over time, influenced by philanthropic activities[21,36]. Although this global trend is widespread, the results highlight spatial variations, notably in Indonesia and the Mediterranean area[38]. Alongside rising temperatures, the study identifies heightened emissions of specific pollutants, including CH_4, CO_2, and N_2O, particularly in Asian regions marked by diverse production and processing industries[44].

The diverse findings concerning climatic factors and air pollutants underscore potential significant impacts on global animal protein availability, particularly considering the interactions with animal production[16]. These findings underscore the essential need to carefully assess the interplay between environmental elements and food resource availability in forthcoming measures aimed at enhancing animal protein access.

The assessment of population density confirms the persistent global demographic explosion[47], except in Japan, which has experienced density reduction due to aging population issues[49]. This population growth exerts pressure on resources, notably land for agricultural use, especially in Asia, exemplified by China's significant rice production[43]. Conversely, Europe faces land occupancy concerns due to urbanization, affecting 72% of the EU population[51]. These findings suggest a gradual decline in available animal protein due to sustained population growth in the examined countries[25,27].

From an economic perspective related to animal proteins, global variations in gross national incomes and protein prices per ton are evident. Despite this variability, countries' incomes are rising, reflecting improved purchasing power primarily due to healthcare services and increasing investments[58]. Concurrently, the prices of animal protein are rising due to heightened import demand, especially driven by avian influenza concerns[28]. Most countries observe increased production of animal proteins, particularly poultry and sheep meat, compensating for declines in pig and beef meat due to swine fever episodes[27]. While these increases help maintain per capita protein levels in most countries, France and Germany face a gradual decline.

Despite availability increases in several countries, the rate of accessible animal protein has generally decreased over the past three decades, indicating a continued supply-demand gap in the face of a growing population[27].

The Linear Mixed Model (LMM) results demonstrate that several parameters influence the progressive protein availability evolution in various countries. These parameters encompass temperature, CH_4, nitrous oxide N_2O, average annual price per ton, agricultural land area, population density, and animal protein production indicators (total protein produced and stock change). These results align with studies by Diallo et al.[16], Tchaker[19], and Caillavet et al.[25], which respectively establish relationships with climatic parameters.

Moreover, the model reveals positive impacts of average annual protein prices, agricultural land area, and total protein production at the national level on available animal protein per capita. The positive influence of protein prices is linked to gross national income, indicating purchasing power. Agricultural land's positive impact stems from its use for livestock feed production, particularly crops like corn, oats, and soy[29]. Furthermore, total protein production enhances national availability, aligning with the increased production's ability to meet demand[69].

Amidst varying explanatory parameters, forecasts depict a declining trend in European animal protein availability by 2030, contrasting with an increase in Indonesia and Japan. These findings resonate with OECD and FAO projections of increased animal protein resources globally, such as beef, pork, poultry, and sheep meat, with projected increments of 5.9%, 13.1%, 17.8%, and 15.7% respectively by 2030 compared to 2018–2020.

However, when compared against protein requirements, it's evident that animal proteins alone won't meet population protein needs by 2030[27]. These results underscore the importance of developing alternative protein food products, particularly dairy and plant-based options[25,61]. As animal protein needs grow with population expansion, the strain on animal resources intensifies. Promoting substitute proteins facilitates policies to reduce meat consumption by 2030, aligning with environmental and animal resource preservation[60]. Many people in tropical regions already rely on plant-based diets that heavily incorporate tropical plants for protein. For instance, legumes like cowpeas (*Vigna unguiculata*) and pigeon peas (*Cajanus cajan*) are common sources of plant-based protein in tropical diets[70,71].

Conclusions

This study highlights the complex interconnection between climatic, demographic, economic and environmental variables that influence the availability of animal protein in Europe and Asia. Indeed, after an in-depth analysis of the different relationships, this study highlights several significant results that deserve special attention. First of all, global warming is confirmed as a global phenomenon, directly linked to human activities. Temperatures have increased significantly in recent decades, with specific regional variations, especially in Indonesia and the Mediterranean area. This highlights the urgent need for concerted action to mitigate the impact of climate change. In parallel, another major concern is the increase in emissions of pollutants such as CH_4, CO_2, and N_2O, mainly in industrial and agricultural areas. The regulation of these emissions must remain at the heart of global environmental strategies and contemporary debates.

Regarding demography, population density continues to grow across the world, putting considerable pressure on natural and animal resources. This population growth poses major challenges for ensuring food security and the availability of animal protein in the years to come. Economically, the results indicate spatial variability in national gross incomes and animal protein prices. The increase in income reflects an improvement in purchasing power, while price fluctuations are influenced by health problems, such as avian flu.

The mixed linear regression models also highlighted the significant impact of certain parameters such as temperature, pollutant emissions, population density and production indicators on the availability of animal proteins. These results highlight the importance of taking these factors into account when planning food and environmental policies.

Finally, forecasts for the next few years indicate an expected increase in the availability of animal proteins in Asia (Indonesia and Japan) (but still below the necessary needs), while in Europe a gradual decrease will be recorded. Faced with these challenges, it is therefore essential to develop innovative strategies with alternative solutions, such as protein substitutes based on dairy products and vegetables, to meet the growing demand while preserving the environment and the health of populations.

Author contributions

The authors confirm contribution to the paper as follows: study conception and design: Dossa KF, Miassi YE; data collection: Dossa KF, Miassi YE; analysis and interpretation of results: Dossa KF, Miassi YE; draft manuscript preparation: Dossa KF, Miassi YE. Both of authors reviewed the results and approved the final version of the manuscript.

Data availability

The data supporting the reported results are available as Supplementary Files and can be obtained upon reasonable request.

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Conflict of interest

The authors declare that they have no conflict of interest.

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