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FOOD SECURITY, HUMAN HEALTH, AND ECONOMY: A HOLISTIC APPROACH TO SUSTAINABLE REGULATION

Purpose. *The research aims to formulate recommendations for sustainable food security regulation taking into account the agriculture intensification's impact on public health, health-associated economic loss, and regional variations of these effects.*

Methodology / approach*. The impact of agricultural intensification on public health was analysed using national and regional (climate zones) data on cancer cases per 100,000 population and mineral fertiliser application per hectare of sown area from the State Statistics Service of Ukraine for 2010–2019. Regression analyses were performed using GRETL 2022c, employing OLS and ARMAX models. Additionally, health-related economic losses from contaminated food consumption in 2020 were estimated based on regional environmental damage assessments and data on environmental damage structure. These assessments informed and guided the suggestions of an organisational and economic framework essential for sustainable food security regulation.*

Results. *Based on global research experiences, we identified a notable positive correlation between cancer morbidity and the application of mineral fertilisers in Ukraine, both on a national scale and within four distinct natural geographical zones. These findings highlight the imperative to reconceptualise the notion of food security by incorporating the dimension of human health. Given the eco-destructive nature of the agricultural environment and the socio-ecological and economic factors influencing public health, we articulate the structural and functional elements of an organisational and economic framework essential for the sustainable regulation of food security.*

Originality / scientific novelty. *The research results underscore the need to redefine the concept of food security to encompass the dimension of human health. Moreover, it evaluates the economic losses related to health state resulting from consuming contaminated food across various natural and climatic zones. It demonstrates that a harmonious coexistence of food security objectives and the preservation of human health can be achieved by developing a suitable organisational and economic framework for sustainable food security regulation.*

Practical value / implications. *The comprehensive assessment of environmental and economic damage to public health caused by contaminated food consumption, considering regional contexts and natural geographical zones, enables determining the scale of environmental, economic and medical risks and, thus, making adequate and optimal management decisions in sustainable food security regulation based on ecologisation of agricultural production.*

Key words: *food security, public health, ecologisation, fertiliser effect, food pollution, cancer morbidity, economic loss, organisational and economic mechanism.*

Introduction and review of literature. Food security – ensuring the physical and economic availability food for current and future populations – is the biggest challenge of modern development. Due to the need to increase food production, intensifying agriculture seems to be the only way to achieve food security goals. Intensive agricultural practices to boost and cheapen food production simultaneously threaten the balance of agroecological systems (Pandey & Diwan, 2018). This results in increased pollution of agricultural resources (elements of natural capital) deteriorating agrarian products and food quality. As the food factor gains importance among the reasons for health deterioration (Shkuratov, 2016; Karintseva, 2018, pp. 113–114; Kubatko & Kubatko, 2019), the efficiency of agricultural policy needs to be assessed through the public health perspective, among others. Finding a balance between the production of sufficient food at affordable prices and the negative impact of agriculture on public health is one of the most challenging issues of sustainable food security regulation.

The issue of food security has recently attracted considerable attention of scientists. Skaf et al. (2020), in their bibliometric research, revealed that over 19,000 scientific papers on food security were indexed in the Web of Science Core Collection between 1990 and 2019 (up to August 2, 2019). Notably, approximately 2,750 papers were indexed in just the first half of 2019 (Skaf et al., 2020). Over the past few decades, the focus of food security research has transitioned from socio-economic aspects such as health, hunger, affordability, and nutrition (in the 1990s and 2000s) to environmental concerns (since the 2000s) (Skaf et al., 2020). While ecological issues and food security problems are inherently linked within the concept of a sustainable food system, they are primarily studied in the context of climate change (Loboguerrero et al., 2020; Pachapur et al., 2020), soil health (Ramankutty et al., 2018), modern agricultural practices aimed at ensuring sufficient food quantity and adequate nutrition (Pérez-Escamilla, 2017; Walls et al., 2019; Green et al., 2020; Bagnall et al., 2021; Strid et al., 2021).

It is essential to recognise that the expected population growth in the coming decades will place an increased burden on agricultural production, potentially escalating its reliance on fertiliser use (Yang et al., 2017). Within this context, the impact of agricultural intensification, combined with the increased use of fertilizers and agrochemicals on the health of the population deserves special attention. Studies on these issues began in the mid-1930s and peaked during the 1970s and 1980s (Senesil et al., 1999).

While the assessment of agricultural impact on public health predominantly centres on the use of pesticides (Bonner & Alavanja, 2017; Budzinski & Couderchet, 2018; Iriti & Vitalini, 2020), it is essential to note that there are existing stringent regulations in place to mitigate associated risks (Iriti & Vitalini, 2020). However, the situation regarding fertilisation is slightly different. Pandey & Diwan (2018), in their exploration of agricultural practices in various regions of India, showed that intensive farming practices can elevate the risk of soil contamination with nitrogen due to excessive fertilisation. This over-fertilisation is often driven by farmers' pursuit of profit and increased yields, disregarding environmental considerations, although farmers are often aware of the ecological consequences of over-fertilisation (Pandey

& Diwan, 2018). On a global scale, concerns about pollution from unsustainable fertilisation practices are becoming increasingly acute. Nitrogen fertilisers, for instance, contribute to the formation of "dead zones" in the Midwest of the USA, result in annual economic losses ranging from EUR 70 to EUR 320 billion in Europe, lead to environmental issues in China and India, and are implicated in the prevalence of cancer diseases (Yin et al., 2020).

In the mid-1970s, researchers observed a correlation between the application of nitrate fertilisers per hectare of arable land and the mortality rate from gastric cancer in Chile (Armijo & Coulson, 1975; Zaldívar & Wetterstrand, 1975; Zaldívar, 1977). A study conducted in Kashmir revealed that 22.3 % of gastric cancer cases were attributable to soil contamination, with 21.6 % and 38.6 % of patients reporting frequent contact with fertilisers and pesticides (Bhat et al., 2015). Furthermore, Hagmar et al. (1991) identified a heightened risk of prostate cancer (approximately 1.5-fold) among male workers who had regular exposure to nitrate fertilisers (Hagmar et al., 1991). Prolonged exposure to chemical fertilisers also results in the accumulation of heavy metals in soils and water, subsequently increasing the risk of cancer within the local population (Senesil et al., 1999; Ciaula, 2016; Mohajer et al., 2013; Song et al., 2018; Bindraban et al., 2020).

Available concentrations of trace elements and the condition of soils affect their uptake by food and fodder plants, influencing the quality of food and drinking water and affecting the population's health (Senesil et al., 1999). This can significantly affect the population's health (Senesil et al., 1999). It's essential to consider that various agricultural practices are employed in different regions, and the diversity of soil types, natural areas, and climatic conditions all contribute to variations in the content of trace elements in soils (Sharpley, 1995; Baligar et al., 2001; Baliuk & Kucher, 2019; Clark et al., 2007; Pandey & Diwan, 2018; Djagba et al., 2019; Balasooriya et al., 2022). Given this diversity, studies investigating the spatial aspects and regional variations in the impact of agricultural intensification on public health are critically important (Pandey & Diwan, 2018).

For instance, Yang et al. (2017) conducted a study in China and found that health costs associated with fertilisation accounted for approximately 0.5 % of agricultural output. Moreover, these health-related costs can vary significantly across different regions, further impacting estimates of economic losses (Yang et al., 2017). This highlights the complex interplay between agricultural practices, public health, and economics, making it crucial to consider these factors collectively in discussions on sustainable food security regulation.

Taking into account the eco- and socially destructive consequences of the movement to achieve food security goals through intensive agriculture is especially relevant for developing countries due to the weakness of institutional and economic-legal mechanisms of agricultural policy resulting in threats to population health (Mishenin et al., 2017; Strochenko et al., 2017; Koblianska & Kalachevska, 2019; Mishenin et al., 2021).

The agro-industrial complex in Ukraine is referenced as a backbone and driver of national economic development and a link to integration into the international financial system (Kolesnyk et al., 2018). Despite the recent increase in agricultural output and exports in Ukraine, food security and sustainable development problems (overcoming hunger and ensuring the sustainability of agricultural production) remain unresolved (Vasylieva & Kruse, 2018; Seheda et al., 2019; Sukhonos et al., 2018; Plastun et al., 2021). In this context, analysing the impact of contaminated agricultural products on public health within the framework of sustainable food security regulation should be an essential issue in Ukrainian science.

I. Skorokhod found a connection between the influence of mineral fertiliser and cancer morbidity in the Rivne region (Skorokhod, 2022). Some scholars estimated the economic losses associated with public health deterioration due to consuming contaminated food (Tsarenko, 1998; Tsarenko et al., 2002). However, the spatial aspects (distribution by natural and climatic zones) of pollution of natural resources caused by agriculture and its impact on public health have yet to be sufficiently studied.

The dimension of food security in relation to health remains a relevant practical and scientific issue, although the decline in research in this field since the 90s is evident (Senesil et al., 1999). As Senesil et al. (1999) note, this is due to a shift in research funding priorities towards climate change issues (Senesil et al., 1999). Without minimizing the importance of the latter, we emphasize that the assessment of the impact of agricultural intensification on the health of the population should be considered in search of balance between healthy food, healthy environment and healthy life.

Regulation of yield-enhancing agricultural practices based on the epidemiological situation and public health estimates (Bonner & Alavanja, 2017) should be a starting point for elaborating sustainable food security policy. For example, the emerging “One Health” concept refers to the health of the population, animals, and the environment in a single systemic context (Garcia et al., 2020), interrelated problems of eco-destructive (contaminated) food production and consumption are mentioned in the “food-environmental” security framework (Shcherban, 2004; Mishenin et al., 2015; Shkuratov, 2016; Koshkalda, 2017). Thus, the implementation of integrated policies targeting various socio-ecological and economic factors of food production and consumption requires an assessment of agricultural production and health relationships based on relevant empirical data. (Buravlov, 2004, pp. 71–73; Garcia et al., 2020; Bindraban et al., 2020).

Therefore, despite the joint efforts of researchers and experts to address the intricate challenges of food security, these issues remain especially acute for agrarian countries that face the adverse consequences of intensified agricultural practices. There is still the need to search for balance between the intensification results: food adequacy and income on the one hand and the anthropogenic impact on the environment and public health on the other. Hence, considering the eco-destructiveness of the agricultural environment and the socio-ecological and economic aspects of public health, it becomes urgent to outline the structural and functional content of the organisational and economic mechanisms for sustainable food security regulation. These issues are addressed in this study.

The purpose of the article. The study aims to elaborate the guidelines in sustainable food security regulation through an assessment of the impact of agriculture intensification on public health and regional variations of such impact.

***Methodology*.** To explore the impact of agricultural intensification on public health, we used the data of the State Statistics Service of Ukraine (collections "Institutions of health care and morbidity of the population of Ukraine" and "Application of mineral and organic fertilisers for crops") for 2010–2019 setting the number of cancer cases which were registered in medical institutions at the end of the year per 100 thousand population as a dependent variable (NCC) and the amount of mineral fertilisers in nutrients in kilograms per 1 ha of sown area as a regressor (FSA). To investigate the spatial variations of fertiliser effect and cancer morbidity, we grouped administrative regions by natural geographical zones according to Maluha's (2008) approach. So, the Polissya zone includes Volyn, Zhytomyr, Rivne, and Chernihiv oblasts, the Forest-Steppe zone covers Kyiv, Vinnytsia, Poltava, Sumy, Ternopil, Khmelnytsky, Kharkiv, and Cherkasy oblasts, the Steppe zone covers Dnipropetrovsk, Zaporizhia, Kirovohrad, Mykolaiv, Odesa and Kherson. The Carpathian Mountain Zone includes Zakarpattia, Ivano-Frankivsk, Lviv and Chernivtsi. We did not analyse the Donetsk and Luhansk regions because of the incomplete data caused by the military conflict. We used the same data for natural geographical zones to explore the relationship between the number of cancer cases and fertiliser exposure. Variables PNCC, FSNCC, SNCC, and MNCC represent the number of cancer cases at the end of the year per 100,000 population, while PMF, FSMF, SMF, and MMF are the number of mineral fertilisers in nutrients in kilograms per 1 ha of sown area in Polissya, Forest-Steppe, Steppe, and Carpathian Mountain Zone, respectively. Table 1 provides the descriptive statistics for the data analysed.

Table 1

Summary statistics, using the observations 2000–2019

Variable	Mean	Median	Min	Max	Std. Dev.	C.V.	Skewness	Ex. kurtosis
NCC	2032.2	2065.5	1567.0	2409.0	278.31	0.13695	-0.25182	-1.2969
FSA	60.800	57.500	13.000	121.00	33.746	0.55503	0.32249	-0.97404
PMF	107.25	109.50	73.000	138.75	21.378	0.19933	-0.083807	-0.85865
PNCC	2084.2	2083.9	1828.1	2244.6	142.41	0.068326	-0.49930	-0.71537
FSMF	99.609	100.00	75.500	127.88	16.050	0.16113	0.31943	-0.42921
FSNCC	2496.3	2487.3	2225.0	2802.4	201.50	0.080720	0.14538	-1.1938
SMF	57.937	52.583	42.167	88.333	14.919	0.25749	1.1787	0.17784
SNCC	2567.2	2606.2	2309.9	2790.7	162.26	0.063205	-0.32033	-1.0225
MMF	111.88	115.50	88.250	125.50	12.623	0.11283	-0.74134	-0.56675
MNCC	1913.5	1916.0	1704.5	2123.9	149.60	0.078181	-0.025108	-1.3344

Source: authors' calculations.

The study of the relationship between the levels of fertiliser application and the cancer incidence rate was made using regression analysis. The Ordinary Least Squares (OLS) method and AutoRegressive Moving Average with eXogenous inputs

(ARMAX) models were run in the GRETL 2022c environment (Baiocchi & Distaso, 2003).

Additionally, we assessed the health-associated economic loss caused by the consumption of contaminated food in 2020 for different natural and geographical zones according to the regional estimates of the average annual environmental damage from pollution (air, water resources) for 2001–2009 (Sotnyk & Kyrychok, 2012; Sotnyk & Kulyk, 2014) and data on the structure of environmental damage (Tsarenko et al., 2002, pp. 83–85; Karintseva, 2018, pp. 137–139).

Referring to the eco-destructive agricultural environment and socio-ecological and economic parameters of public health, we construct the foundational elements of the organisational and economic framework essential for sustainable food security regulation.

Results and discussion. The agro-industrial complex is among the predominant causes of environmental pollution and the resulting food sources contamination. Sector's contribution to environmental degradation is estimated to range between 35 % and 40 % on a comprehensive scale, with a more substantial impact observed in the context of land resources, accounting for more than 50 % of the overall environmental burden. Furthermore, the pollution of surface water bodies, constituting a crucial component of the ecological system, is also significantly influenced by the agro-industrial complex, averaging around 35 % to 40 %. Overall, the agro-industrial complex is seen to be responsible for approximately three-fifths of the total environmental pollution (Trehobchuk, 1995).

It is important to note that the agriculture share in the world GDP averages 3.1 %, in Ukraine is 9.8 %, the world leaders are the Central African Republic (55.8 %), Sierra Leone (54.7 %), and Chad (53.2 %) (Agricultural…, 2016). There is a high level of land ploughing in Ukraine, which reaches 56 % (in developed European countries – it does not exceed 35 %) (Biznes Tsenzor, 2019). At the same time, there are 0.38 hectares of arable land per capita (in particular, in Poland – 0.38 ha, France – 0.30 ha), and Ukraine – 0.64 ha). According to current estimates, only 1 in 10 hectares of productive land has a normal ecological status. The influence of the agro-industrial complex extends to almost 80 % of the total area of Ukraine (Trehobchuk, 1997). Undoubtedly, eco-destructive factors of agricultural management cause significant environmental and economic damage from environmental pollution and degradation, primarily concerning public health loss.

Agriculture is considered as a recipient, which not only perceives the effects of industrial emissions and other anthropogenic impacts but also, along with the agro-food industry, is one of the essential intensive factors of environmental pollution and harmful effects on public health that should be examined in the format of food security provision. Agricultural chemicalization is carried out at almost all agricultural and agro-industrial production stages. The ratio of environmental and economic damage from chemical pollution, according to (Tsarenko et al., 2002, p. 53), can be characterised in the sectoral context as follows: the damage from agriculture exceeds the loss from light industry more than 38 times, and from the agro-industrial complex – 14 times.

Thus, all these eco-destructive processes (factors) of agricultural production significantly change the human habitat, which is increasingly becoming artificial and anthropogenic. Inefficient use and ruthless exploitation of agricultural resources (in particular, land) have a catastrophic impact on soil fertility and environmental quality. Decreasing soil fertility leads to increasing chemical use, attraction of new arable lands and large-scale increase of anthropogenic agricultural landscapes. In addition to reducing the share of natural environment in the biosphere, the circulation of substances is disrupted, hazardous wastes are accumulated, etc. (Ramad, 1981, p. 117). In an eco-destructive environment, the adaptive functions of the human body are disrupted, resulting in the threat of unfavourable health changes. Global pollution caused by chemical compounds has a negative impact not only on the present generation but may also affect future generations (Mereniuk, 1984, p. 64).

The results of hygienic studies prove the potential hazard of toxicological, carcinogenic, mutagenic and teratogenic effects of contaminated food. The morbidity rate of the European population based on the food factor is characterised by the following data: diseases depending on the nutrition nature – 41 %; diseases in the development of which nutrition factor plays the leading role (due to food quality and safety) – 38 %, other diseases – 18 % (Robertson et al., 2000).

Food composition has an unfavourable content of food additives and a full range of hazardous substances used in agricultural technologies and technological schemes for processing raw materials. The methodological approach to a quantitative assessment of the ecological and economic risk of health deterioration is based on the assumption that initial food raw materials, in the processing, can transfer the pollution hazards (in particular, as a result of cultivation with mineral fertilisers and pesticides) to the finished food product, enhancing and burdening it with various food additives use due to modern technologies.

Mechanisms of hazardous substances introduction into food are well known. They can result from insufficient consideration of the territory's natural and climatic features and the use of polluting agricultural technologies, thereby increasing the risk of food contamination (Kupinets, 2010, p. 37).

It should also be emphasised that in order to determine the compensatory and socio-economic measures and projects based on environmental and economic damage estimation caused by chemical pollution, including the corresponding direct financial compensation for losses, it is necessary to develop tools for determining these losses, first of all – the health level deterioration through the increased morbidity assessment. The most essential element of such tools is the mechanism of quantitative assessment of health decline under the influence of agro-destructive factors.

The use of mineral fertilisers and plant protection products (especially in case of non-compliance with doses and application rules, as well as the use of cheap little-studied herbal preparations) leads to the accumulation of hazardous substances in the soil and products, which are harmful to the human health, causing different diseases, in particular oncological (International Agency…, 2020; Mishenin et al., 2022).

Figure 1 presents the relationship between Ukraine's mineral fertilisers application and cancer dynamics over almost twenty years.

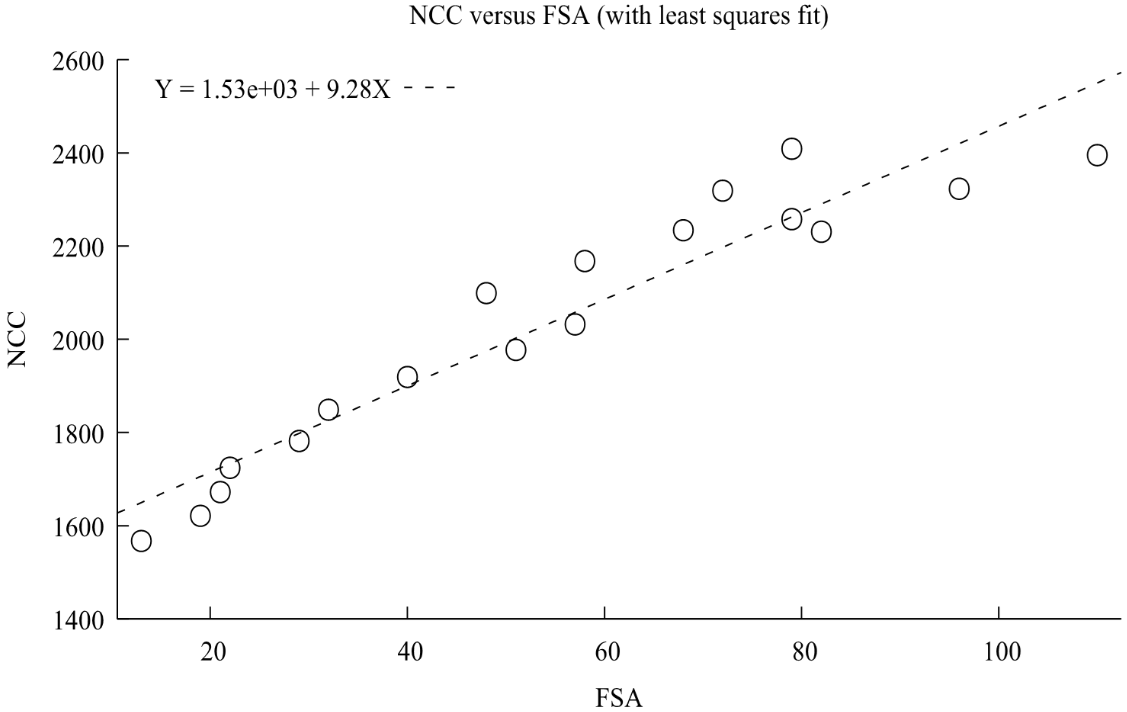


Figure 1. Relationship between application of mineral fertilisers (FSA) and number of cancers in Ukraine (NCC) for 2000–2019

Source: authors' calculations based on (Health care…, 2021; Application…, 2021).

The estimates for a linear regression model, elucidating the relationship between the cancer incidence rate per 100,000 population and the number of mineral fertilisers applied per hectare of sown area in Ukraine, revealed a statistically significant relationship between fertilisation levels and disease incidence rates (Table 2). However, it is imperative to acknowledge that the quality of the model has been thoroughly tested, including assessments of the Rho statistic and Durbin-Watson statistic. These tests showed the presence of autocorrelation within the dataset, thereby rendering the ordinary least squares (OLS) method ineffective for parameter estimations.

A comprehensive analysis was conducted to address the autocorrelation issue, encompassing the examination of partial autocorrelation function (PACF) and autocorrelation function (ACF) correlograms. Additionally, the Breusch-Pagan test was administered to investigate the autocorrelation phenomenon further. The results of this analysis confirm a significant correlation at a lag of 1 for both autoregressive (AR) and moving average (MA) components. Considering these observations, it has become evident that alternative modelling approaches are warranted. Consequently, two potential models, ARMAX (1, 0) and ARMAX (1, 1), were deemed suitable for describing the behaviour of the variables under consideration. The estimations of the parameters for these models are presented in Table 2.

When examining the parameters of the model (Table 2), it should be emphasized that all three models demonstrate a noteworthy and statistically significant relationship between the application of mineral fertilisers and the incidence of cancer with a confidence level of 99%. Nevertheless, when considering the direct influence of fertilisation on disease incidence, the ARMAX models show a slightly lesser immediate effect. However, these models show superior performance in capturing the underlying data patterns, as the adjusted R statistic indicates.

Table 2

Model parameter estimates

Model	OLS	ARMAX (1,1)	ARMAX (1,0)
Constant	1528.838*** (45.4847)	1607.79*** (113.394)	1613.43*** (117.475)
FSA	9.28290*** (0.746823)	7.16284*** (1.95488)	7.12445*** (2.15058)
phi_1	n/a	0.835015*** (0.193791)	0.805274*** (0.216877)
theta_1	n/a	−0.0870659 (0.262707)	n/a
R-squared	0.906159	0.948234	0.947528
Adjusted R-squared	0.900294	0.941331	0.944248
F(1, 16)	154.5014	n/a	n/a
F p-val	1.23e-09	n/a	n/a
rho	0.631141	n/a	n/a
Durbin-Watson	0.733589	n/a	n/a
Log-likelihood	−105.0486	−100.5077	−100.5591
Akaike criterion	214.0973	211.0153	209.1181
Schwarz criterion	215.8780	215.4672	212.6796
Hannan-Quinn	214.3428	211.6292	209.6092

Note. ***denotes p-value <0.01.

Source: authors' calculations.

ARMAX (1, 0) outperforms other candidate models when evaluated using information criteria such as the Akaike Information Criterion (AIC), Schwarz Bayesian Information Criterion (BIC), and Hannan-Quinn Criterion (HQIC). This suggests that this model strikes a favourable balance between model complexity and its ability to explain observed data. In particular, ARMAX (1, 0) elucidates approximately 94.4 % of the variation in the dependent variable, signifying remarkable explanatory power. The model can be presented as follows:

$$\widehat{NCC_t} = 1613.43 + 0.805 NCC_{t-1} + 7.124 FSA_t \,, \qquad (1)$$

where *t* is the period (year).

In summary, the model (1) reveals that the incidence of cancer cases in the current period (t) is influenced by two key factors: the number of diseases in the previous period (NCCt-1) and the number of mineral fertilisers applied per hectare of sown area in the current period (FSAt). This observation highlights the temporal interaction between disease incidence and fertilisation practices. Furthermore, it is noteworthy that a marginal increase in fertiliser application by 1 kg per hectare leads to a corresponding rise in the number of diseases, specifically by 7.12 cases per 100,000 people. This quantifies the direct impact of mineral fertiliser application on disease incidence, highlighting its significance in public health.

It is also worth emphasising that the specified model almost matches the available data, as shown in Figure 2. This alignment between the model and the empirical data demonstrates the effectiveness of the model in identifying the underlying dynamics of the relationship between mineral fertiliser application and cancer incidence, providing valuable insights for further research and policy considerations.

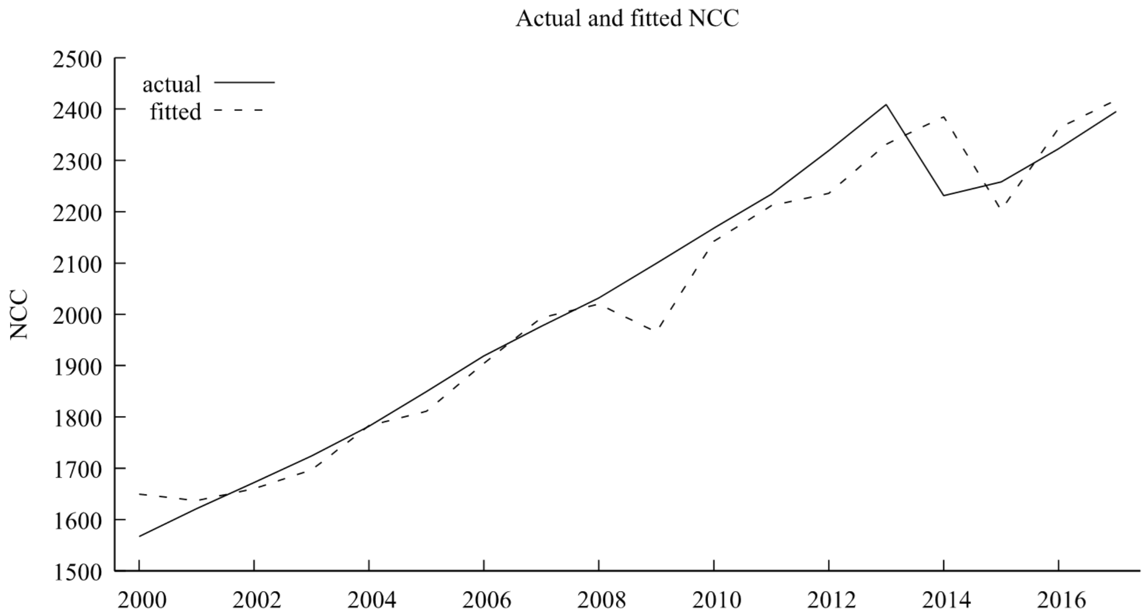
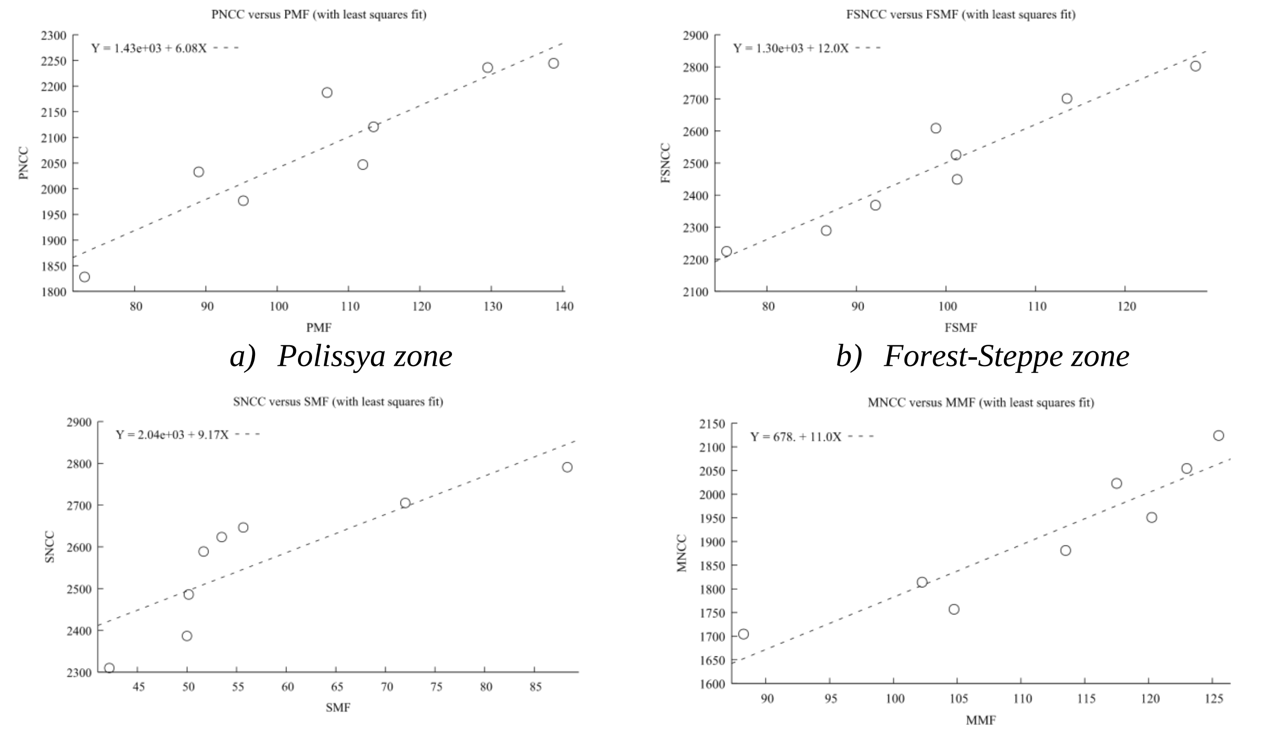


Figure 2. Number of cancer cases in Ukraine (NCC) for 2000-2019: actual and modeled data

Source: authors' calculations based on (Health care…, 2021; Application…, 2021)

Recognizing that the amount of mineral fertilisers applied depends on various factors, including soil type, is critical. Different natural geographical zones cover diverse soil compositions. To evaluate the environmental and economic ramifications of the heightened morbidity attributed to agricultural chemicalization within regional contexts, we analysed the correlation between cancer incidence rates and the volume of mineral fertilisers within distinct natural zones. The XY scatterplot visually portrays these data patterns, as illustrated in Figure 3. This visual representation helps to elucidate the relationships and differences observed in different geographic regions, thereby contributing to a comprehensive understanding of the interplay between agricultural practices in concrete natural conditions and public health outcomes.

A visual inspection of the data reveals that linear correlations are observable in the Polissya, Forest-Steppe, and Carpathian Mountain zones. However, when considering the Steppe zone, the relationship between variables appears to be more complicated and requires further investigation. The outcomes of estimating these linear dependencies using the Ordinary Least Squares (OLS) method are presented in Table 3.



a) Polissya zone *b) Forest-Steppe zone*

c) Steppe zone *d) Carpathian Mountain zone*

Figure 3. Relationship between application of mineral fertilisers and number of cancers in Ukraine for natural zones, 2010–2017

Source: authors' calculations based on (Health care…, 2021; Application…, 2021).

Table 3

OLS linear regression estimates for different natural sones

Natural zone	Polissya	Forest-Steppe	Steppe	Carpathian Mountain
Dependent variable	PNCC	FSNCC	SNCC	MNCC
Constant	1431.86*** (120.963)	1304.75*** (156.710)	2035.78*** (142.220)	677.613** (197.083)
PMF	6.08254*** (1.10875)	n/a	n/a	n/a
FSMF	n/a	11.9618*** (1.55568)	n/a	n/a
SMF	n/a	n/a	9.17179*** (2.38646)	n/a
MMF	n/a	n/a	n/a	11.0473*** (1.75191)
Sum squared resid	23596.69	26185.26	53236.58	20539.66
S.E. of regression	62.71190	66.06217	94.19535	58.50878
R-squared	0.833774	0.907866	0.711131	0.868892
Adjusted R-squared	0.806070	0.892510	0.662986	0.847041
F(1, 6)	30.09544	59.12240	14.77067	39.76377
P-value (F)	0.001535	0.000253	0.008527	0.000742
Log-likelihood	−43.30919	−43.72555	−46.56375	−42.75419
Akaike criterion	90.61838	91.45110	97.12749	89.50839
Schwarz criterion	90.77726	91.60998	97.28638	89.66727
Hannan-Quinn	89.54678	90.37950	96.05589	88.43679
rho	−0.064421	0.306779	0.606521	−0.167179
Durbin-Watson	1.985467	1.360238	0.560782	1.970058

Note. ***denotes p-value <0.01, **denotes p-value <0.05.
Source: authors' calculations.

The assessment of the models included rigorous testing for heteroscedasticity, normality of residual distribution, and autocorrelation. For the Polissya and Carpathian Mountain zones, these tests did not reveal any misspecifications, indicating that the models adequately represent the relationships within these regions.

In the case of the Forest-Steppe zone, the Durbin-Watson statistic suggests a potential presence of autocorrelation. However, statistical tests provide reasons to accept the null hypothesis of no autocorrelation at the 90 % significance level (p-value = 0.0690703). Thus, although autocorrelation is indicated, it does not reach statistical significance at the 90 % level.

Conversely, for the Steppe zone, the Durbin-Watson statistic strongly suggests the existence of autocorrelation, with positive autocorrelation being confirmed (p-value = 2.60399e-05). This caused the need for a more detailed study of the model specification, which was based on the evaluation of correlograms and the Breusch-Pagan test. The results of these analyses led to the determination of autoregression with two lags and a moving average with one lag as suitable components. Consequently, the estimation of the ARMAX model (2, 1) was conducted (Table 4).

Table 4

Estimates of model parameters for Steppe zone

Model	ARMAX (2, 1)
Dependent variable	SNCC
Constant	2253.07*** (47.4928)
SMF	5.50618*** (0.639701)
phi_1	1.47726*** (0.157078)
phi_2	−0.843100*** (0.154980)
theta_1	1.00000** (0.455382)
R-squared	0.992523
Adjusted R-squared	0.986915
Log-likelihood	−37.24812
Akaike criterion	86.49624
Schwarz criterion	86.97289
Hannan-Quinn	83.28143

Note. ***denotes p-value <0.01, **denotes p-value <0.05.

Source: authors' calculations.

The thorough analysis of model residuals concerning normality, heteroscedasticity, and autocorrelation revealed no discernible irregularities. Consequently, the ARMAX (2, 1) model, compared to the OLS model (Table 3), emerges as a superior choice for elucidating the variability within the studied variable. Additionally, it exhibits superior performance with respect to various information criteria.

Thus, in various natural and climatic zones, a strong and positive connection between the use of mineral fertilizers and the incidence of cancer has been firmly established. In the Polissya, Forest Steppe, and Carpathian Mountain zones, these relationships are respectively represented by the following equations (2), (3), (4):

$$\widehat{PNCC} = 1431.86 + 6.08PMF, \tag{2}$$

$$\widehat{FSNCC} = 1304.75 + 11.96FSMF, \tag{3}$$

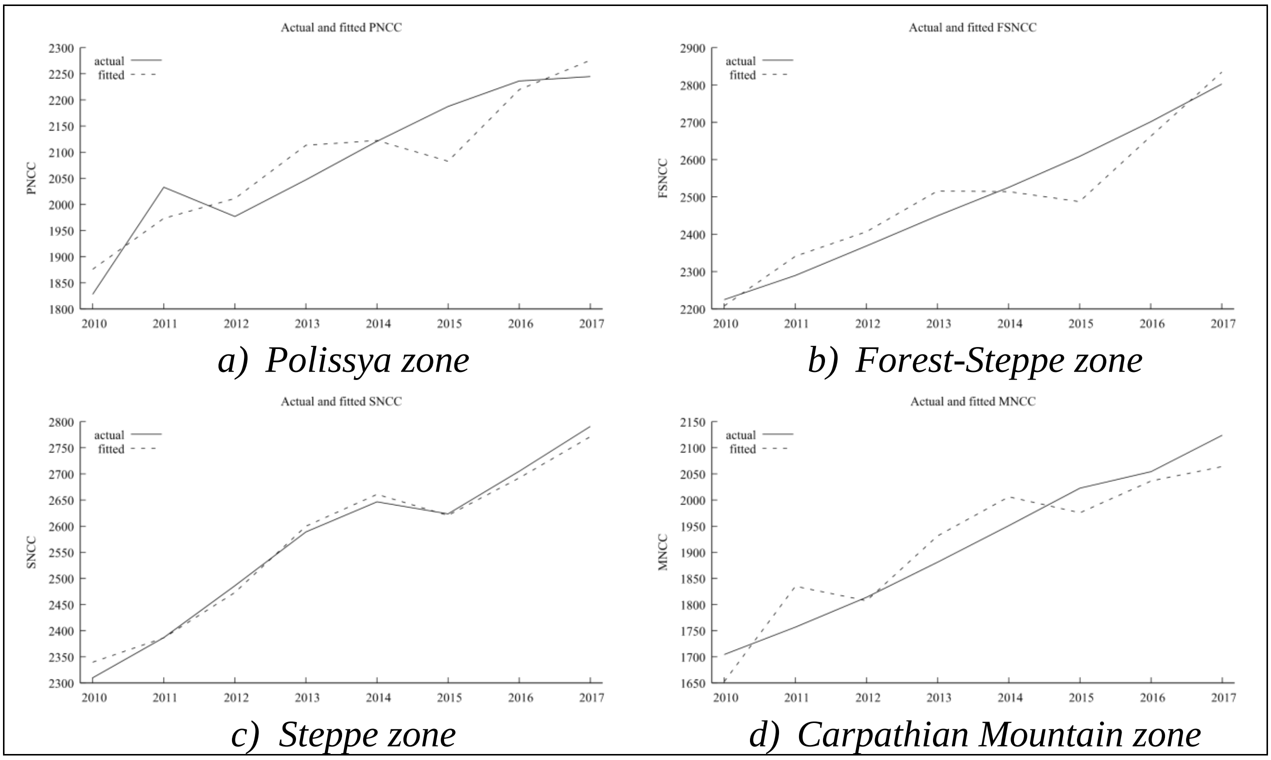
$$\widehat{MNCC} = 677.61 + 11.05MMF, \tag{4}$$

For Steppe zone the relationship is as follows:

$$\widehat{SNCC}_t = 2253.07 + 1.48SNCC_{t-1} - 0.84SNCC_{t-2} + 1.0\varepsilon_{t-1} + 5.518SMF_t, \tag{5}$$

where ε_{t-1} is the error term; t is the period (year).

The specified models agree quite well with the existing data (see Figure 4).



a) Polissya zone *b) Forest-Steppe zone*

c) Steppe zone *d) Carpathian Mountain zone*

Figure 4. Comparison of observed and model-predicted cancer cases in natural zones, 2010–2017

Source: authors' calculations based on (Health care…, 2021; Application…, 2021).

In the Polissya zone, the specified model (Equation 2, Table 3) effectively accounts for 80.6 % of the variability in cancer cases and reveals a substantial positive correlation between the dependent variable and the performance factor. The regression coefficient indicates that for every 1 kg/ha increase in mineral fertilisation, there is an associated rise of 6.08 cases per 100,000 of the population in cancer incidence.

Similarly, within the Forest Steppe zone (Equation 3, Table 3), the relationship between the amount of applied fertilisers and cancer cases shows a positive and statistically significant association. A 1 kg/ha increase in fertiliser application is linked to a rise of 11.96 cancer cases per 100,000 population. The model accounts for 89.3 % of the variability in the dependent variable.

In the Carpathian Mountains region (Equation 4, Table 3), the model indicates that 84.7 % of the variation in cancer cases can be attributed to variations in the number of mineral fertilisers applied. A 1 kg/ha increase in fertiliser application corresponds to a rise of 11.04 cancer cases per 100,000 population.

The ARMAX (2, 1) model specified for the Steppe zone (Equation 5, Table 4) demonstrates exceptional explanatory power, elucidating 98.7 % of the variability in cancer cases. This variation is influenced by the number of cancer cases observed one and two years ago, showing positive and negative relationships, respectively, and the amount of mineral fertilisers applied in the same period. Specifically, a 1 kg increase in fertiliser application per hectare of sown area results in a corresponding rise in 5.51 cancer cases per 100,000 population.

The regression analysis results show a close and positive relationship between fertilisation and cancer incidence rates in Ukraine, both on average and within four distinct natural geographical zones. Notably, the Forest Steppe and Carpathian Mountain zones experience a more pronounced negative impact, whereas the Steppe and Polissya zones exhibit a relatively lower effect than the national average.

The outcomes of the quantitative analysis of the relationship between cancer incidence rates and mineral fertiliser application across different natural geographical zones of Ukraine hold significant methodological and practical implications. They serve as a crucial information and analytical database, offering valuable insights for determining indicators of environmental and economic losses. These findings are essential in guiding policies and mechanisms to regulate sustainable food security.

Notably, estimates of economic loss resulting from the consumption of contaminated food are relatively scarce, and only approximate figures are available. Previous scientific research conducted at the end of the 20th and the beginning of the 21st century (Tsarenko, 1998, p. 116; Shcherban, 2004, p. 143) indicated economic losses attributed to contaminated food consumption in Ukraine, ranging from 2,100 to 13,700 million USD.

Building upon the findings of earlier studies, the present research incorporates data on the average annual comprehensive assessment of environmental damage stemming from environmental pollution (including air and water resources) across different regions for the years 2001–2009 (Sotnyk & Kyrychok, 2012). Furthermore, it draws upon information related to the typical structure of environmental losses (Tsarenko et al., 2002, pp. 83–85; Karintseva, 2018, pp. 137–139) to facilitate an approximate evaluation of public health damage attributable to the consumption of contaminated food within distinct natural geographical zones, as outlined in Table 5.

It is important to recognize that the methodology for comprehensive evaluation of total environmental and economic damage to public health, encompassing environmental and economic risks, still needs to be fully elaborated. Consequently, the estimates provided should be regarded as approximations. Nevertheless, such assessments offer valuable insights into the extent of environmental, economic, and medical risks in a regional context. As a result, these assessments empower decision-makers to formulate appropriate and optimal strategies for regulating sustainable food security.

Table 5

Environmental and economic damage caused by the environmental pollution and food contamination, million USD, 2020*

Region/zone	Pollution damage	
	environment	food
Polissya zone		
Volyn region	501.2	410.1
Zhytomyr region	918.9	751.8
Rivne region	808.8	661.8
Chernihiv region	829.2	678.5
Forest Steppe zone		
Kyiv region	1250.2	1023.0
Kyiv	764.5	625.5
Vinnytsya region	673.2	550.8
Poltava region	649.0	531.0
Sumy region	629.4	515.0
Kharkiv region	901.3	737.4
Ternopil region	195.7	160.1
Khmelnytsk region	440.2	360.2
Cherkasy region	475.0	388.6
Steppe zone		
Dnipropetrovsk region	3620.4	2962.2
Donetsk region	4936.5	4039.0
Luhansk region	1700.7	1391.5
Zaporizhzhia region	1331.7	1089.6
Kropyvnytskyi region	333.3	272.7
Mykolaiv region	296.5	242.6
Odesa region	808.7	661.7
Kherson region	414.8	339.4
Carpathian Mountain zone		
Lviv region	1004.9	822.2
Ivano-Frankivsk region	934.9	765.0
Chernivtsi region	376.7	308.2
Zakarpattia region	514.7	421.1
Together by regions	25337.4	20709.0

Note. * In terms of the US dollar at the average annual exchange rate in 2020.

Source: estimated by authors based on (Sotnyk & Kyrychok, 2012; Sotnyk & Kulyk, 2014; Tsarenko et al., 2002, pp. 83–85; Karintseva, 2018).

The socio-ecological and economic aspects related to environmentally detrimental agricultural practices highlight an environmentally destructive agrarian environment. This environment significantly influences public health and food security, as illustrated in Figure 5.

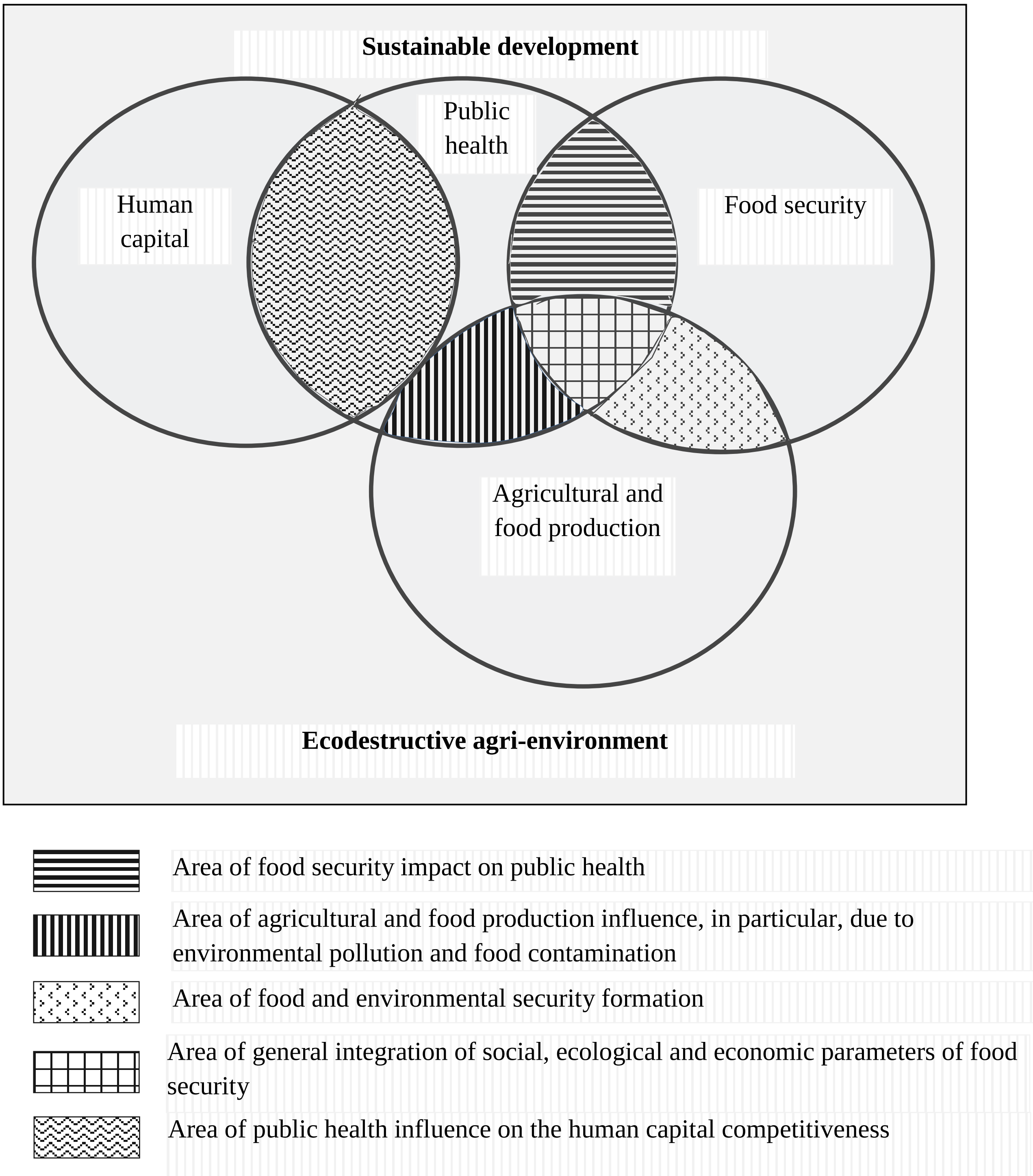


Figure 5. Relationship between public health and food security in the format of eco-destructive agricultural environment and sustainable development

Source: authors' development.

The presented scheme (Figure 5) shows the importance of assessing population health within the framework of sustainable food security regulation. It emphasizes the necessity for a paradigm shift towards considering health in the context of both food and environmental security. To some extent, this shift highlights the imperative to incorporate greener practices in agriculture and food production. Moreover, it prompts a closer examination of the intricate relationship between public health and human capital recognised as a driver of economic growth (Melnyk et al., 2021; Kryvenko & Ovcharenko, 2014; Tarkhov et al., 2012).

In light of the growing food demands of society, it is clear that self-regulation within an environmentally destructive agricultural environment has limitations and needs to meet these demands. Consequently, this requires a fundamental shift in the conceptual approaches and principles underpinning sustainable agriculture and food security across various spatial development levels, including the global, national, regional, and local scales (Plastun et al., 2021; Vasylieva & Kruse, 2018; Stehnei et al., 2018).

While increasing food production is often seen as the primary requirement for enhancing food security, it is essential to recognise that this is just one aspect of a multifaceted challenge. The rate of food production growth must correspond to the principles of sustainable socio-economic development and environmental sustainability in agricultural practices. We are talking about food and environmental security, a strategic goal that now shapes the policy landscape of sustainable farming and agri-food complex development. Therefore, these considerations raise the question of how to approach sustainable food security regulation, particularly within the food and environmental security framework or through ecological sustainability.

Food and environmental security involves the creation of environmentally sustainable food production systems that rely on a healthy environment, innovative technologies, and the responsible use of agrarian natural and resource potential (Burkinskiy & Kovaleva, 2002; Kupinets, 2010, p. 17).

The main goals of formulating strategic directions for regulating sustainable food security with integrating ecological considerations can be summarised as follows:

- achieving the sustainable use of agricultural natural resources and reducing artificial loads (including chemical inputs) on the contemporary environmentally damaging agri-natural environment through innovative agricultural ecologisation;
- ensuring consistent production of an adequate food supply to meet current and contingency requirements, including the capacity for food imports;
- attaining social and economic food sufficiency and affordability;
- provision of high-quality and environmentally safe food to preserve the nation’s health and genetic diversity, promoting increased life expectancy, and facilitating the reproduction of a competitive human capital;
- sustaining environmentally friendly food consumption infrastructure;
- promoting competitive and ecologically responsible food production development.

Hence, the primary criterion for evaluating the effectiveness of achieving these objectives should be the state of public health, influenced by factors such as dietary caloric content, balanced nutrition, the environmental quality of food, and the socio-ecological living conditions of the population within the context of an environmentally destructive environment. Realising the objectives and tasks of food security ecologisation necessitates establishing an appropriate organisational and economic framework for regulating sustainable food security, as illustrated in Figure 6.

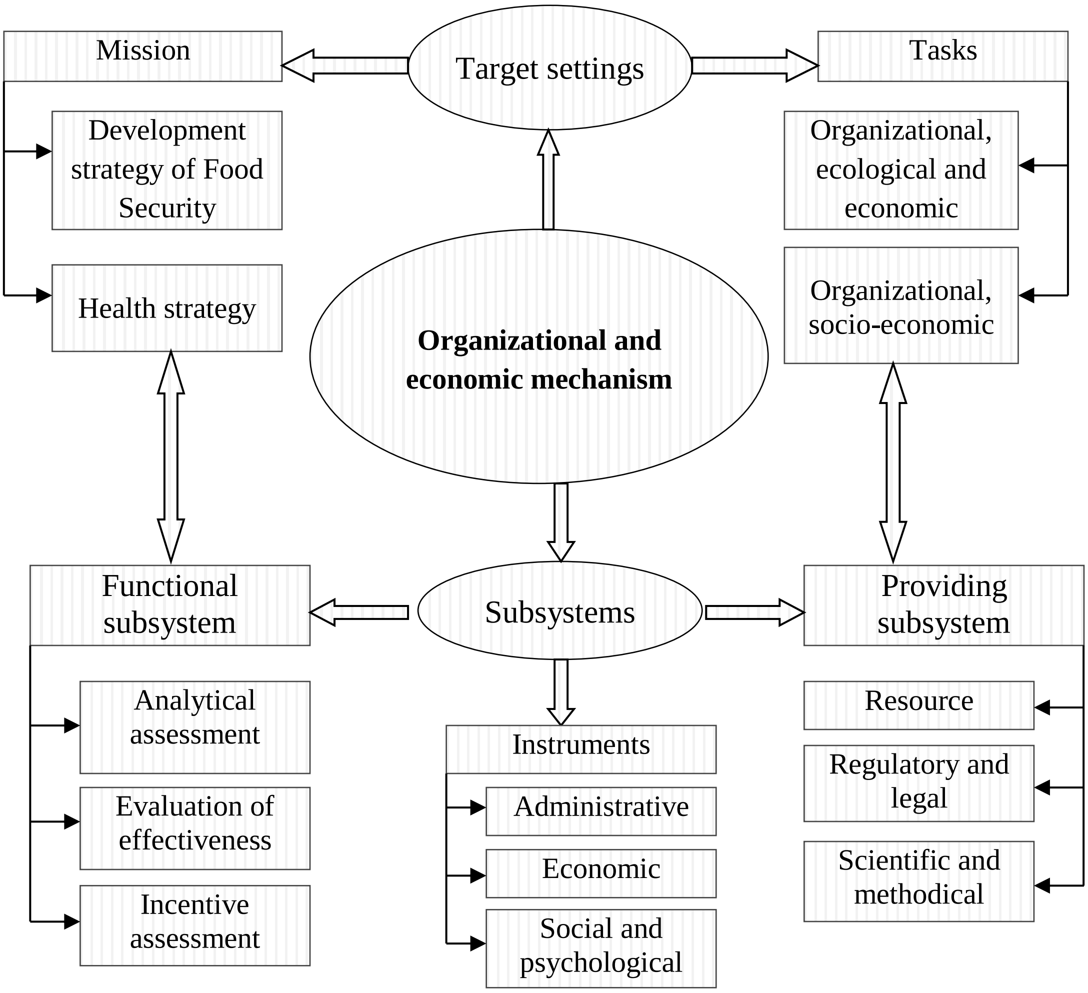


Figure 6. Structural and functional formation of the organizational and economic mechanism for sustainable food security regulation

Source: authors' development taking into account (Khvesyk, 2014, pp. 238).

The Figure 6 presents the comprehensive framework for the structural and functional development of the organisational and economic mechanism for regulating sustainable food security. It pays significant attention on the socio-ecological and economic dimensions of assessing public health within strategic guidance. Although delving into the detailed contents of each component of this mechanism requires a separate study, it is necessary to comment on some general and specific points.

The organisational and economic mechanisms for regulating sustainable food security are an integrated and comprehensive system encompassing various forms, methods, tools, and instruments. It has organisational, institutional, environmental, economic, and socio-environmental impact on the economic behaviours of agricultural actors and stakeholders involved in food security ecologisation. The main purpose of this impact is to increase socio-ecological and economic efficiency, the effectiveness of food production and consumption, to protect public health and to improve ecologically harmful agricultural environment.

A core function of the organisational and economic mechanism for regulating sustainable food security is to harmonise the socio-environmental and economic needs and interests of businesses, society, and citizens engaged in food production and consumption. This involves resolving emerging conflicts and specific socio-environmental and economic contradictions. The mechanism should operate within a well-defined regulatory framework, focusing on promoting food security ecologisation. The activation of incentive instruments must be accompanied by strong institutional support, encompassing the revision of environmental standards, legislative enhancements, the establishment of institutions to facilitate environmentally friendly economic activities, adaptations to organisational management systems, and the use of varios environmental management tools and investment project management.

Given these considerations, there should be a concerted effort to prioritise regulatory and legal support for sustainable food security regulation, considering socio-environmental and economic parameters for assessing public health.

In the existing project, it is necessary to consider the issue of the impact of agricultural production on the health of the population. The strategy recognizes the importance of improving mechanisms for state support of agriculture and fisheries, promoting principles of healthy nutrition, and ensuring compliance among producers of agricultural products, raw materials, and food with environmental, sanitary-epidemiological, veterinary, and other requirements (Ministry of Economy…, 2020). However, a significant concern is the need for a holistic agricultural sector development strategy in Ukraine.

The "Strategy for the Development of the Agricultural Sector of the Economy until 2020" (Cabinet of Ministers…, 2020) raises specific issues, such as the lack of motivation for producers to comply with agri-environmental requirements, reducing the sector's environmental impact (although without prioritising), incentivising rational natural resource use, and setting target indicators for agricultural management (without incorporating socio-ecological and economic indicators). While the strategy promotes the development of organic farming, it needs clear socio-environmental guidelines. It addresses the range of socio-ecological and economic challenges facing the agricultural sector in the context of sustainable food security regulation. The strategy does not take into account the aspect of health and does not explore the creation of an integrated organizational and economic mechanism for agricultural production ecologisation.

The Law of Ukraine "About pesticides and agrochemicals" (Verkhovna Rada…, 1995) emphasises the priority of health preservation and environmental protection over economic benefits associated with using pesticides and agrochemicals. Nevertheless, this law does not address the need for estimating environmental and economic damages resulting from public health deterioration. Similarly, the Law of Ukraine "On Basic Principles and Requirements for Organic Production, Circulation, and Labeling of Organic Products" (2018) defines relevant directions for state policy in this area. However, it does not explicitly consider environmental food security assessment.

The regulatory framework for ensuring sustainable food security demands careful consideration of organisational and economic mechanisms for ecologisation, with a strong emphasis on health assessment. The interdisciplinary complexity and the widespread impact of environmentally destructive factors on public health at all stages of agricultural production and consumption present substantial methodological, scientific, methodological, and practical challenges in the development of appropriate policy measures (Tsarenko et al., 2002; Kupinets, 2010, pp. 238; Bonner & Alavanja, 2017; Bindraban et al., 2020).

The results obtained in this study confirmed previous data that highlighted the close association between fertiliser application and adverse health effects, particularly in terms of cancer incidence and mortality (Armijo & Coulson, 1975; Zaldıvar & Wetterstrand, 1975; Zaldívar, 1977; Senesil et al., 1999; Ciaula, 2016; Mohajer et al., 2013; Yang et al., 2017; Pandey & Diwan, 2018; Song et al., 2018; Bindraban et al., 2020; Skorokhod, 2022). The assessment of public health dependency on eco-destructive factors associated with agricultural chemicalization and the consumption of contaminated food relies on various socio-ecological and economic parameters that lack standardisation and often have local relevance. Consequently, each mathematical model developed for this purpose is to some extent specific and always has potential for refinement.

The lack of data on the impact of fertilizers and cancer cases in Ukraine, especially in a regional context, to some extent limits the use of the results of this study. However, the study of the relationship between fertiliser application and cancer incidence rates may continue to evolve and improve. This is the initial stage of research into the socio-ecological and economic assessment of losses associated with excessive chemicalization of agriculture, so further research is fully justified. These localised relationships are already found practical application in current and predictive assessments of healthcare effects arising from reduced agrochemical loads (Skorokhod, 2022).

Methodological and practical tools for assessing the environmental and economic damage to public health due to the consumption of contaminated food still needs to be developed. (Karintseva, 2018; Kubatko, 2017; Yang et al., 2017). Expanding the information-analytical database with comprehensive damage assessments, in particular by natural and geographical zones, opens up opportunities for sustainable regulation of food security, including mechanisms of financial compensation.

The structural and functional framework of the organisational and economic mechanism for regulating sustainable food security is subject to varied interpretations in terms of component types and content (subsystems, sub-mechanisms) (Shcherban, 2004, pp. 177–178; Shkuratov, 2016, p. 95; Kupinets & Zhavnerchyk, 2016, pp. 160–163). To a large extent, the construction of this mechanism depends on its integration function and level of application (global, national, regional, local). In conclusion, it is important to emphasize that the organisational and economic mechanism for regulating sustainable food security should be oriented toward ecologisation and public health assessment.

Conclusions. The results of the study made it possible to draw the following conclusions:

1. The analysis highlights the necessity and potential of socio-environmental research to establish the correlation between the use of mineral fertilisers and cancer incidence rates, especially in the context of natural geographical zones. The constructed regression models, which examine the relationship between cancer incidence rates and the quantity of mineral fertilisers, are specific to four natural geographical regions of Ukraine (Polissya, Forest Steppe, Steppe, and the Carpathian Mountains). These models provide valuable insights into the natural indicators of environmental and economic losses and the impacts of changing morbidity rates. These insights can be used in developing mechanisms for managing and regulating sustainable food security.

2. Regression analysis using national data and data classified by four natural geographic areas demonstrates a statistically significant and strong positive association between fertilisation and cancer incidence rates. On average, an increase of 1 kg of mineral fertilisers per hectare leads to an increase of 7.12 cancer cases per 100,000 of the Ukrainian population. The specified ARMAX (1, 0) model explains 94.4 % of the variability in the national context. Notably, the adverse impact of fertilisation is more pronounced in the Forest Steppe and Carpathian Mountain zones, where fertiliser exposure results in 11.96 and 11.04 cancer cases per 100,000 population, respectively. Linear regression models account for nearly 90 % of the observed variation in morbidity. Conversely, the impact of fertilisation on cancer morbidity is less pronounced in the Polissya and Steppe zones, where the effects estimated are 6.08 and 5.51 oncological incidents per 100,000 population, respectively. In the Steppe zone, the number of cancer cases is influenced by fertilisation and morbidity rates observed in previous periods, whereas in Polissya, fertilisation directly determines 80.6 % of morbidity variance.

3. The comprehensive evaluation of environmental and economic damage to public health due to consuming contaminated food in the regional context and natural geographical zones facilitates the quantification of environmental, economic, and medical risks. This, in turn, enables the formulation of informed and optimal management decisions in sustainable food security regulation centred on the ecologisation of agricultural production.

4. Given the limitations of self-regulation within the environmentally destructive agricultural environment and its inadequacy in addressing the growing food demands of society, there is a practical imperative to reconsider fundamental principles and conceptual approaches to the future of sustainable agricultural production and food security. Consequently, with a focus on public health, the question arises regarding the necessity of regulating sustainable food security within the food and environmental security framework and its ecologisation.

5. The structural and functional framework of the organisational and economic mechanism for sustainable food security regulation is characterised by its comprehensive interconnection of components, ensuring its effectiveness. The implementation of such a mechanism will facilitate environmentally sustainable food consumption and contribute to the improvement of public health.

In conclusion, it is crucial to emphasise that one of the critical tasks for making informed strategic decisions in support of a system for regulating sustainable food security is the consideration of all socio-environmental and economic factors and the results of their interactions. By considering pollutants and their impact on the environment, agricultural production, and public health, meaningful positive changes in environmental food security can be achieved.

Prospects for further research. It is essential to acknowledge that the methodology for assessing the total environmental and economic damage to public health (environmental and economic risk) needs to be developed. As a result, these estimates are subject to a high degree of approximation. The assessment of public health's dependence on eco-destructive factors related to agricultural chemicalization and the consumption of contaminated food uses diverse socio-ecological and economic parameters that lack standardisation and are often specific to local conditions. Consequently, each mathematical model developed for this purpose remains specific and inherently open to improvement. Thus, future research should be aimed at clarifying and increasing the accuracy of measuring the scale of environmental, economic and medical risks in the regional context, which will allow more informed and optimal decisions to be made in the context of mechanisms for regulating sustainable food security.

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