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The role of technology in the water–energy–food nexus. A case study: Kerinthos, North Euboea, Greece

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The water–energy–food (WEF) nexus is a basic element of prosperity, yet it is not equally distributed on the land. Human progress has optimized the function of the WEF nexus to bridge the inequality gap. In order to understand this progress, this study compares the preindustrial and modern agricultural practices in an area in Greece. Interviews were conducted with an elderly man who lived in the 1950s, and the process was quantified in units of WEF. The same procedure was also carried out with modern farmers for modern agricultural practices. In comparing the past and present agricultural processes, it is observed that today, a farmer can feed approximately 100 times more people. This feat has been achieved as modern practices push the land with energy sources in multiple ways (fuels and fertilizers). However, energy indices such as energy ratio, net energy gain, specific energy, and energy productivity do not seem to be improved. Furthermore, farmers prefer to pump underground water for irrigation, instead of utilizing the nearby river, as was done in the past when the river provided both energy to the watermill and an abundance of water for irrigation. In addition, as the price of wheat is dependent on the stock market, even in 2023, there are risks to food security, the cultivation of wheat was not economically efficient for farmers in this area in 2023.

KEYWORDS

water–energy–food nexus, technology, economy, resources, human progress

1 Introduction

In modern societies, the key to prosperity is considered economic thriving. However, if our focus remains solely on financial abundance without considering the availability of essential resources, such as water, energy, and food, our priority of a thriving economy might not fulfill the fundamental requirements for survival (Spiegelberg et al., 2017; Simpson and Jewitt, 2019). This concept is illustrated in the ancient Greek myth of Midas (Chatzimpiros et al., 2007; Koutsoyiannis and Mamassis, 2021), who, due to his ability to turn everything into gold, found himself trapped and starved (Roller, 1983; Sargentis and Koutsoyiannis, 2023).

In our perspective, the essence of prosperity resides in recognizing and understanding the intricate interplay among water, energy, and food systems, collectively referred to as the water–energy–food (WEF) nexus (Allouche et al., 2015; Al-Saidi and Elagib, 2017; Wichelns, 2017; IRENA, 2019; Al-Saidi and Hussam, 2021; Siganou et al., 2022; The Water, Energy & Food Security Resource Platform, n.d.; WEF Background, n.d.). While the term WEF nexus was formally introduced by The World Economic Forum Water Initiative (2011), the conceptualization and acknowledgment of the interconnectedness among these elements had been identified earlier in scholarly work by Koutsoyiannis et al. (2009). The essence of the WEF nexus lies in the holistic examination of these critical dimensions, emphasizing that water, energy, and food are not isolated entities but rather intricately linked components of a larger system.

The importance of the WEF nexus becomes increasingly evident as a growing body of literature is dedicated to its systematic study (Simpson et al., 2022; Sargentis et al., 2022a,d). Over the past decade, scholars and experts have recognized the multifaceted nature of the interactions within the WEF nexus, acknowledging its role in shaping sustainable resource management strategies. This comprehensive approach ensures that the implications of decisions in one dimension are thoroughly understood in the context of the entire nexus. By considering these dimensions together, we gain insights into the complex nexus of relationships and dependencies, paving the way for more informed and integrated approaches to resource management (Yang and Yamazaki, 2013; Food and Agriculture Organization (FAO) of the United Nations, 2014; Leck et al., 2015; Chang et al., 2016; Endo et al., 2017; Albrecht et al., 2018; Zhang et al., 2018; Hamidov et al., 2022; Simpson et al., 2022).

In the broader context, the WEF nexus has evolved as a conceptual framework that can be traced back to the foundations of Integrated Water Resources Management (IWRM). The WEF nexus represents an extension and refinement of the IWRM concept, incorporating additional dimensions, such as energy and food systems, to comprehensively address the intricate connections and interdependencies among water, energy, and food.

In the framework of the WEF nexus, water plays a dual role by serving as a resource that can generate energy through hydropower and enhance food production through irrigation. The nexus is further strengthened as energy inputs, such as oil for machinery and fertilizers, that contribute to facilitating food production. Additionally, oil or electricity is employed in the process of pumping underground water, highlighting the interconnected nature of these elements. Moreover, within this intricate nexus, food assumes a multifaceted role as both an energy source for both livestock and humans and as a carrier of water. The interdependencies and synergies among water, energy, and food highlight the comprehensive and integrated nature of the WEF nexus (Daher and Mohtar, 2015; Daher et al., 2020; Lee et al., 2020; Sargentis et al., 2021). Moreover, there is an ongoing discourse regarding the various dimensions to incorporate into the analysis of the nexus, such as land (Water-Energy-Food Nexus for Sustainable Land Management, n.d.), society (Urbinatti et al., 2020), and ecosystems/environment (European Commission, n.d.).

The foundation of civilization can be traced back to the agricultural revolution in the 10th millennium B.C. During this period, people recognized the significance of the WEF nexus and understood that increased water supply (via irrigation) and energy (utilizing animals) led to higher food production, allowing more people to be sustained with less land (Coughenour et al., 1985; Singh et al., 2002; Schnepf, 2004; Smil, 2004a,b; Canakci et al., 2005; Davis and Hatfield, 2007; Jean-Richard et al., 2015; Jiang et al., 2019; Smith, 2019; Iliopoulou et al., 2022).

However, the distribution of the WEF nexus resources across the world is not uniform. This study delves into the inequities in the distribution of rainwater across Greece's expanse of 131,957 km^2. While acknowledging the pivotal role of water in the WEF nexus, it is imperative to elucidate that the nexus's effectiveness extends beyond just water availability. The multifaceted nature of the WEF nexus encompasses various sectors and interconnections, emphasizing that prosperity hinges on the optimized synergy and surplus accumulation of its elements. Contrary to historical periods where the nexus may not have operated as efficiently, the contemporary understanding highlights the significance of considering the intricate relationships among water, energy, and food resources.

This study has a dual objective: First, it aims to contribute to the ongoing discussion on superabundance, a concept likely introduced by Tupy and Pooley (2022). This term typically refers to a state of excess or surplus in various aspects of life, potentially encompassing resources, wealth, or overall wellbeing. Second, the study seeks to document the advancements and changes that have occurred in Greece over the last century, with a specific focus on the village of Kerinthos in North Euboea.

To achieve this, the research centers on the firsthand account and insights provided by a local resident, Demetris Kougias, who was born in 1938. Kougias's recollections of the 1950s, particularly regarding the way of life and agricultural practices, serve as valuable qualitative data. These insights are then translated into quantifiable values related to water, energy, and food. By comparing these values with the conditions in the same area in the 2020s, the study aims to illuminate the progress made by the local community and the broader evolution of Greek society in terms of human wellbeing and societal development throughout the past century.

2 Methodology

The inequalities of rainwater distribution in Greece are reviewed, and the disparities in the WEF nexus are illustrated in a near-average rainfall in a Greek province.

Initially, the function of the WEF nexus and the social and living standards in the 1950s were quantified, with data collected through interviews from an interviewee, who was born in 1938. Subsequently, the agricultural practices and wheat production were described and analyzed, and they were converted into energy units. Given that a significant portion of energy inputs involved animals, and considering that healthy and robust animals require food, our calculations incorporated the area needed for cultivating animal feed and the energy required for the cultivation process of these areas. Additionally, the energy and time necessary for maintaining water infrastructures were included. The energy inputs and outputs of the overall process were derived by summing up these factors. Regarding water, the energy needed to maintain and operate the infrastructure was calculated, along with the energy produced from the water through the watermill, and the available water for irrigation (Figure 1A).

Second, modern practices in wheat production and the role of the WEFnexus in the case study area were quantified through *in situ* research and interviews with modern farmers. Detailed descriptions of the process, time requirements, fuel consumption for each step, the types of fertilizers employed, and the anticipated production were provided by the modern farmers. Fuels and fertilizers were then converted into energy units, allowing for the determination of the energy inputs and outputs of the entire process. Regarding water, the

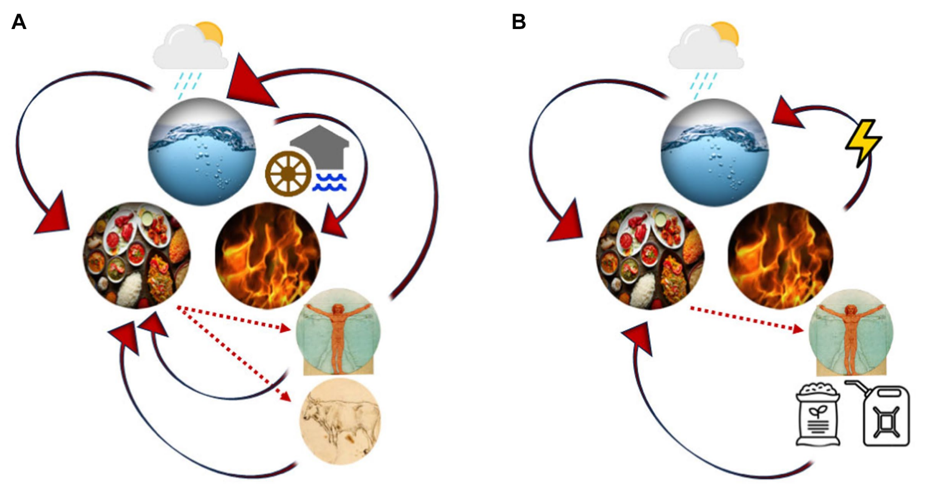

FIGURE 1
A schematic workflow of the methodology **(A)** 1950s and **(B)** 2020s. Notice that the removal of certain links (arrows) in **(B)** with respect to **(A)** as well as the replacement of certain elements.

energy required by the typical aquifer horizon for pumping was calculated, as well as the available water obtained for irrigation (Figure 1B).

Based on the provided data, energy indices (including energy ratio, net energy gain, specific energy, and energy productivity) were derived. These indices serve as evaluative measures for the energy efficiency of the cultivation processes in the 1950s and 2020s (Singh et al., 2007; Ziaei et al., 2015; Gökdoğan and Sevim, 2016; Ansari et al., 2018; Moradi et al., 2018; Ioannidis and Koutsoyiannis, 2020). In the 1950s, energy inputs were derived from animals and humans, and in the 2020s, the energy inputs were from fuels and fertilizers. Energy outputs are calculated by the conversion of the production of the cultivation in energy units (usually calories) to MJ (Singh et al., 2007; Shahin et al., 2008; Nasseri, 2019).

The energy ratio (ER) is the energy we gain from the produced cultivation to the input energy that is provided to the produced cultivation. It is calculated by the following formula (Equation 1):

$$\mathrm{ER} = \frac{\text{Output Energy}\left(\text{MJ ha}^{-1}\right)}{\text{Input Energy}\left(\text{MJ ha}^{-1}\right)} \tag{1}$$

Net energy gain (NEG) is the energy we gain from the produced cultivation subtracted from the input energy. It is calculated by the following formula (Equation 2):

$$\mathrm{NEG} = \text{Output Energy}\left(\text{MJ ha}^{-1}\right) - \text{Input Energy}\left(\text{MJ ha}^{-1}\right) \tag{2}$$

Specific energy (SE) is a ratio between the input energy and the produced edible wheat in weight units. It is calculated by the following formula (Equation 3):

$$\mathrm{SE} = \frac{\text{Input Energy}\left(\text{MJ ha}^{-1}\right)}{\text{Output Quantity}\left(\text{kg ha}^{-1}\right)} \tag{3}$$

Energy productivity (EP) is the ratio between the produced edible wheat in weight units and the input energy. It is calculated by the following formula (Equation 4):

$$\mathrm{EP} = \frac{\text{Output Quantity}\left(\text{kg ha}^{-1}\right)}{\text{Input Energy}\left(\text{MJ ha}^{-1}\right)} \tag{4}$$

According to the above equation, an optimized crop has maximum ER, NEG, and EP and minimum SE.

Finally, to assess the living standards of the 1950s, the time cost of wheat production is summarized, the production is converted into wheat wage, and a comparison is made with the current wheat wage (Sargentis et al., 2022a,d). Additionally, the financial cost of the present cultivation process is calculated, the earnings of farmers are determined, and a financial evaluation is presented.

A limitation of this study was that, due to the scarcity of individuals who were present in the 1950s, only one interviewee was included in the above analysis. Additionally, the embodied energy of the creation of machinery, tools, and infrastructures for modern farming was not calculated. Furthermore, despite the efforts made to evaluate the same area of the WEF and land nexus in the 1950s and 2020s, the inequalities of WEF and imponderable factors introduced uncertainty in the results. For instance, comparing a highly productive year in the 1950s, characterized by abundant water, with a less productive year due to drought in the 2020s, would lead to inaccurate estimations.

It is important to clarify that this study does not aim to offer a precise comparison. The calculations presented in the following sections serve a practical purpose in providing a broad estimate of the scale of various elements considered in the WEF nexus. Instead, the objective was to convey a general impression, substantiated by numerical values, regarding differences that can be easily grasped. Consequently, the results were summarized by presenting average values and highlighting the dynamics of the WEF nexus in the 1950s and 2020s in the order of magnitude.

3 Inequalities of the WEF and land nexus in Greece

As the elements of the nexus are correlated, the abundance or shortage of one part is indicative of the entire nexus. Water is a primary part of the nexus, and even if it is necessary to have infrastructure to exploit water, the availability of surface water eventually depends on rainfall. Recent research (Koutsoyiannis et al., 2023a,b) shows the geographical distribution of the daily average rainfall in Greece.

As a case study, the cultivation of wheat and the role of the WEF nexus in the village of Kerinthos, North Euboea, Greece (38°48′33.00″N; 23°26′42.87″E) is investigated.

Taking into account that rainfall signifies the wealth of an area, the depicted data in Figure 2A, illustrating the average quantities of rainfall among different areas in Greece, was analyzed using a commercial geographical information system. In order to show the inequalities of rainfall and in addition to the histogram shown in Figure 2B (green line) which entails subjectivity and lacks detail and accuracy, the inequalities are also quantified in Figure 2B (blue line) with the estimated probability density. The latter was calculated from the newly introduced statistical tool of knowable moments (K-moments), which can provide smooth empirical representations of the distribution function, which, in turn, can yield point and interval estimates of the density function at a large number of points or even at any arbitrary point within the range of the available observations (Koutsoyiannis, 2022). Figure 2B indicates substantial spread in the geographical distribution of water in Greece, with the annual average per day ranging from 1 to 7.3 mm. Kerinthos has a close-to-average rainfall (1.8 mm per day or 657.0 mm annually; Greek's average: 2.2 mm per day or 797.8 mm annually). Given the scope of the study, it is noted that there have been no discernible trends in rainfall over the past few decades (Koutsoyiannis et al., 2023a,b).

Water constitutes one aspect of the nexus, yet additional inequalities arise due to variations in energy sources and land fertility across different areas. In traditional agricultural settings, ingenious practices evolved in regions with limited rainfall, such as the Cyclades. These areas, characterized by arid conditions (average rainfall of 1 mm per day or 365 mm annually), saw the development of seeds and crops that were adapted to thrive with minimal water requirements (Peliti, n.d.). The cultivation of varieties capable of producing small fruits without relying on irrigation was a testament to the resilience of Greek agriculture in the face of challenging environmental conditions (Gkisakis, 2011). Additionally, as the soils were rocky, agricultural cultivation involved the construction of dry-stone walls that retained the soil, ensuring that the land became as fertile as possible (Zepou and Matsaganis, 2024). Today, these areas are touristic resorts, and agricultural activity is no longer common.

As the inequalities of the nexus are critical for the cultivation methods, the description of the WEF nexus for the entire Greece is impossible. Henceforth, in the subsequent sections, we opt to conduct a case study in Kerinthos, North Euboea, where individuals are actively engaged in agriculture.

4 The function of the WEF nexus in Kerinthos

Until the beginning of the 20th century, the land in Euboea belonged to few landowners. The inhabitants called kolligi (κολλήγοι) were living by cultivating the land of the landowners and by giving half of the crop to them. This social system is considered feudalism (Dariveris, 2023; Sargentis et al., 2022b).

After the Asia Minor catastrophe (1922), (Langouranis, 2015), refugees came to Greece and the population of the village Kerinthos (*ca.* 250 inhabitants) was doubled. The Greek state formed the productive landscape of this region between 1930 and 1950, by buying some of the land from landowners and consolidating 550 ha (plain and barren areas) (Sargentis et al., 2022b). In each family (*ca.* six members) was given 3 ha in plain fields and 3 ha in barren areas (Figure 3).

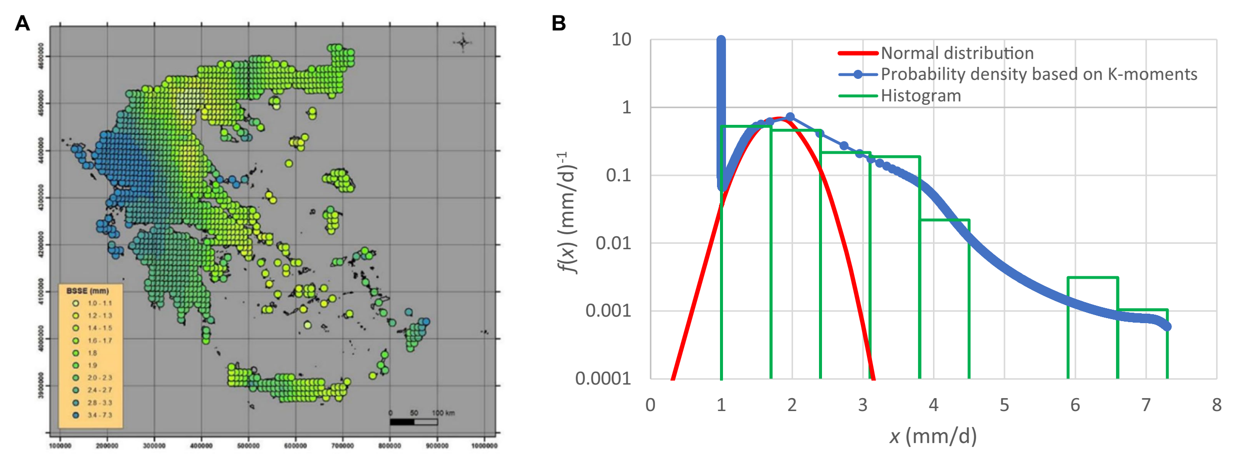

FIGURE 2
(A) The geographical distribution of the daily average rainfall; **(B)** probability density of rainfall estimated from K-moments.

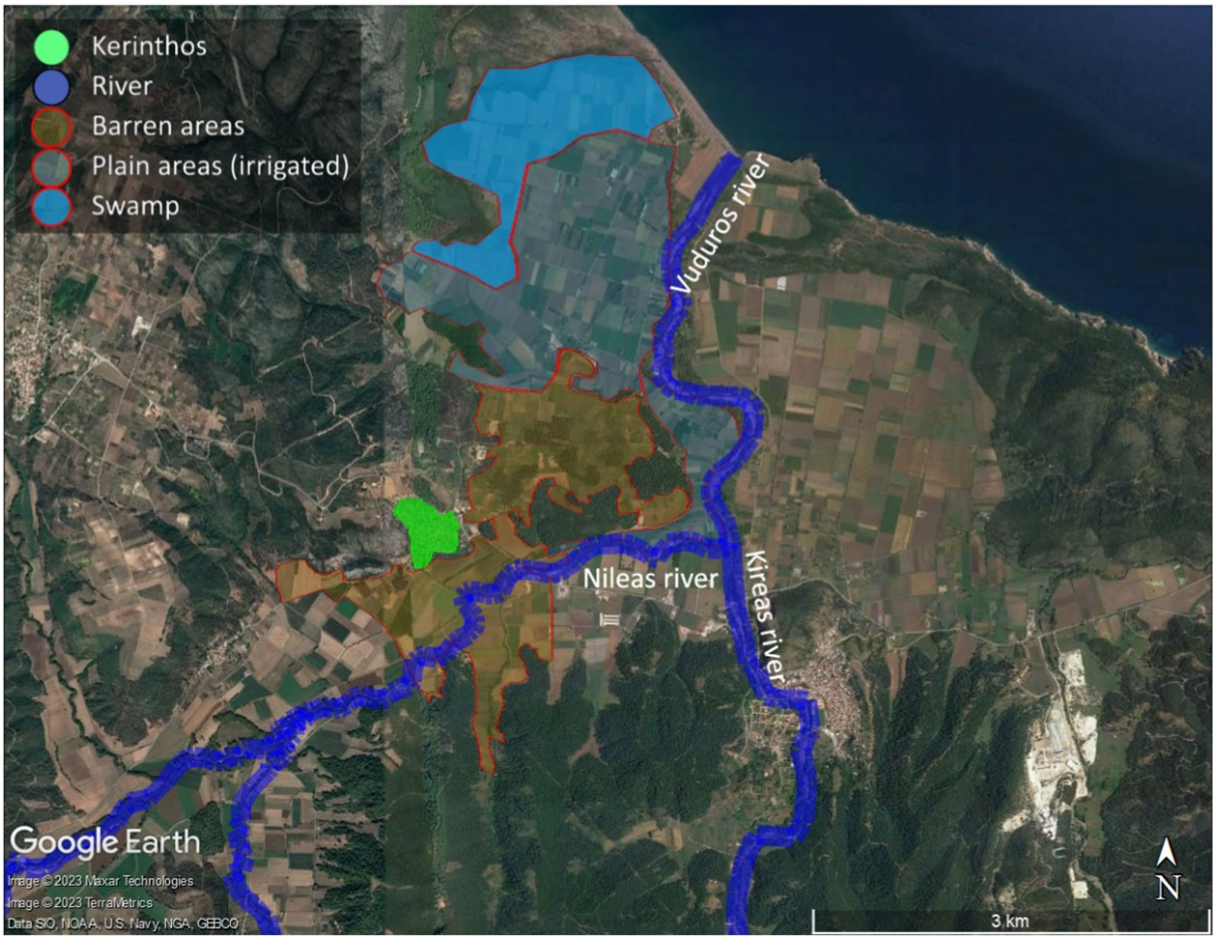

FIGURE 3
Village Kerinthos; hydrographic network nearby; consolidation areas. Source: Google Earth Pro (2021) after adaptation.

4.1 Agricultural practice in the 1950s

The production of wheat is dependent on weather conditions. It varied from a minimum of 320 to a maximum of 1,280 kg/ha. The expected yield was between 650 and 1,025 kg/ha. The production was doubled in plain areas as the land was more fertile. The local expression that describes the variance of the production is "το χωράφι είναι ξεσκέπαστο εργοστάσιο" (English translation: "an agricultural field is an open-air factory").

Working hours were in local expression: "από ήλιο σε ήλιο," translated to English as follows: "from [*sic*]sun (rising) to sun (set)," i.e., 12 h per day on average, using primitive tools (Figures 4, 5). Considering that the intensive work of adults amounts to 4 kWh/day and animal work is 28 kWh/day (Brody and Trowbridge, 1937; Ward et al., 1980; de Ridder and Wagenaar, 1986; Kander and Warde, 2011; Chandrakar et al., 2013; Sargentis et al., 2020a), it is estimated that the total energy in traditional wheat farming was approximately 1,950 MJ/ha with 70% contributed by animals. This value incorporates communal work for dam construction, farrow cleaning, and energy for cultivating animals' food. The working period for 1 ha was 72 days.

Surplus for trading came from the rest cultivations (2 ha) in plain areas. In addition, the protein needs of villagers (Kc et al., 2018) were met by domestic animals (hens, pigs, and goats) and the systematic hunting of wild animals and fishing. The habit of consuming domestic animals for food remains to date (Figure 5C).

4.2 The function of watermill

According to the field observation, the water flow of the Nileas River in August 2023 was approximately 0.35 m^3/s (Figure 6A). Near the river, there is a watermill (late 19th century). It is estimated that the energy from water to watermill was approximately 130 kWh per day (Figures 6B,C), and the fee to the mill was 10%.

For 10–15 days in spring, the villagers was to the Nileas River to build a makeshift dam with tree trunks (δέση του ποταμού; English translation: tie of the river) (Figure 6). Every winter, the dam got destroyed by floods.

The water went by "μυλαύλακο"; English translation: "furrow for watermill," 3.95 km to the watermill from the route indicated in Figure 7 and then irrigated 295 ha in the plain. All the farmers of the village were working approximately 10–15 days in the spring to clean the furrow. One villager was responsible for sharing the water in the fields.

FIGURE 4
(A–E) Snapshots from a video of August 2023 with interviewee reaping with a scythe; **(F)** interviewee with scythe on his shoulder.

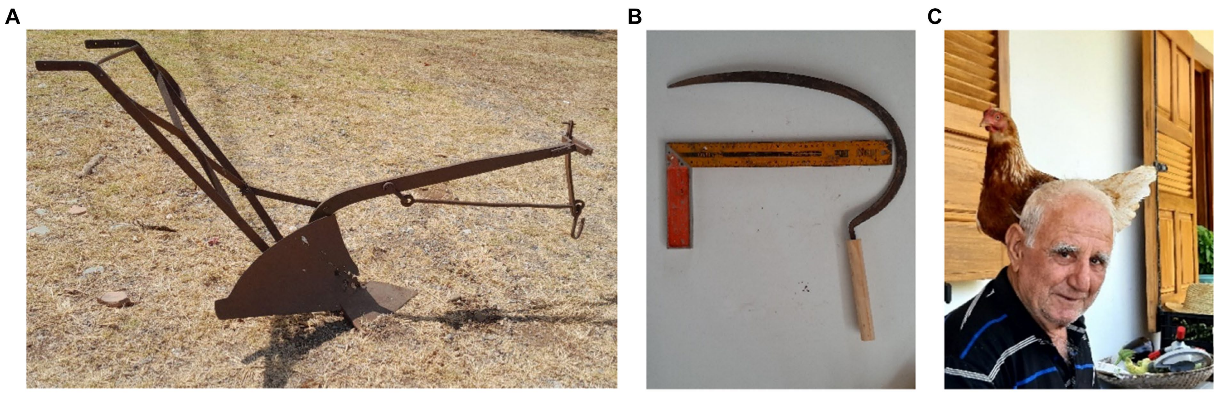

FIGURE 5
Interviewee's **(A)** plow, **(B)** sickle, and **(C)** interviewee with a hen on his shoulder (2021).

4.3 Modern agricultural practice

Detailed descriptions of the modern cultivation methods of wheat, time requirements, fuel consumption for each step, the types of fertilizers employed, and the anticipated production were provided by the modern farmers, Nikos Thomas and Athanasios Drakopoulos.

In the studied area, the energy required is 45.5 GJ/ha, a value obtained by counting the fuel needed for plowing (30 L oil per ha), cultivation (20 L oil per ha), sowing (25 L oil per ha), sprinkling (100 L oil per ha), reaping (75 L oil per ha), and the energy contained in the nitrogen fertilizers (600 kg or 36 GJ/ha) (IEA, 2021; Kirkmalis et al., 2023; Fertilizers Europe, n.d.). The time needed for performing the following actions in 1 ha land is plowing takes 2–3 h, cultivation takes three-quarters of an hour, sowing takes one and a half hours, sprinkling takes 1 h, and reaping takes one and a half hours. However, in the area of the case study, the estates are scattered (the average estate is approximately 1 ha). Therefore, the farmer has to transport the machinery and tools to another estate for each hectare. As this process requires time, the average time taken for each step of the cultivation process is estimated to be 1 day. Consequently, the working period for 1 ha is estimated to be approximately 5 days. The production in barren areas varies between 2,500 and 7,000 kg/ha, and the expected yield is between 3,500 and 4,000 kg/ha.

In plain areas, the yield is doubled as land is more fertile at the additional cost of irrigation. In order to irrigate the plain, the farmers pump groundwater from an aquifer 15 m below the ground level. The average irrigation per hectare is 6,000 m^3/year which means that each year, the needed energy for each irrigated period is approximately 100,000 kWh, 360 GJ, or approximately 1 GJ/ha.

FIGURE 6
(A) River near the dam, August 2023 ($Q = 0.35\,m^3/s$); **(B)** the aqueduct of the watermill; **(C)** the watermill.

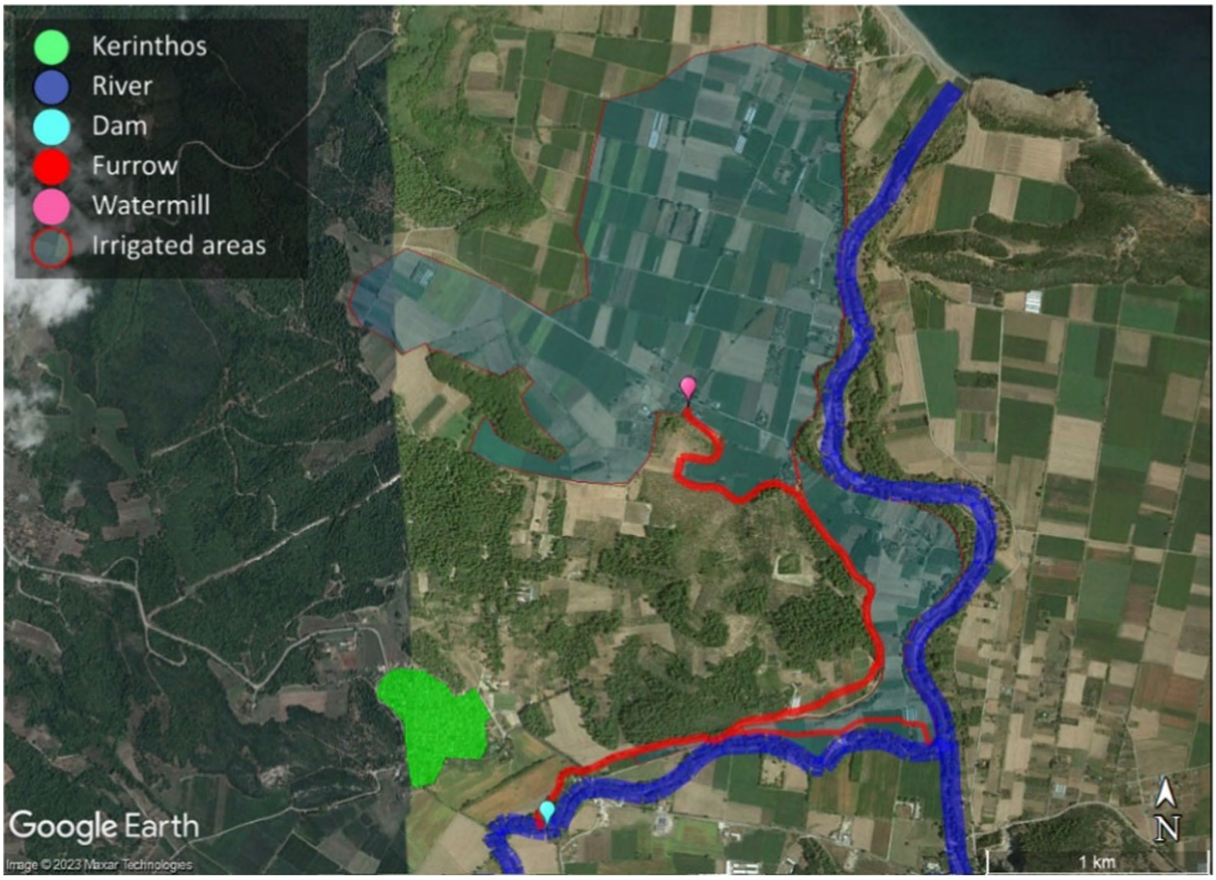

FIGURE 7
Village Kerinthos and the traditional infrastructures for the support of the WEF nexus in the 1950s. Source: Google Earth Pro (2021) after adaptation.

5 Results and discussion

The comparison of the range of wheat production, energy ratio, net energy gain, specific energy, and energy productivity between the cultivation processes in the 1950s and 2020s in barren areas is depicted in Figure 8. Figure 8A illustrates that within the same area, one farmer in the 2020s produced a significantly greater amount of food than 1950s. However, the energy indices presented in Figures 8B–E evaluating the energy efficiency of production indicated that the increased food abundance results from the ample energy supplied to the land in the form of fuels or fertilizers, rather than being a consequence of optimized and efficient farming practices by the skilled farmer.

This is probably due to the abundance of energy that does not create the necessity for optimization. For instance, as illustrated in

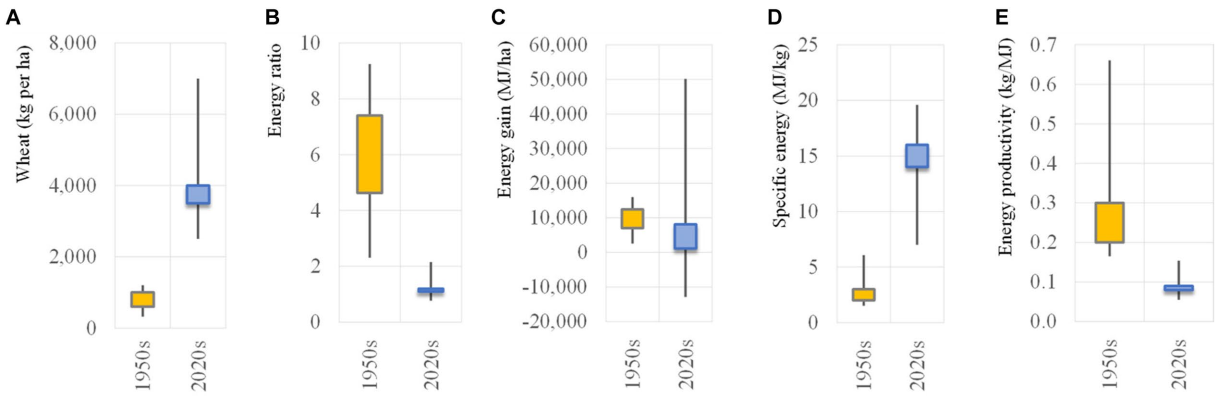

FIGURE 8
(A) Wheat production; **(B)** energy ratio; **(C)** net energy gain; **(D)** specific energy; **(E)** energy productivity.

Figure 1, in the 1950s despite a modest investment in human energy by the villagers to upkeep the furrow for the watermill (45 GJ/year), there was an abundance of water (10 hm^3/year) for both irrigation and the generation of energy in traditional watermill (170 GJ/year). Today, even if water and hydraulic energy are still there, the water from the river is not utilized and farmers prefer to use electricity to pump from groundwater aquifer consuming 350 GJ/year, which gives approximately 2 hm^3/year water for irrigation.

As wheat is the base element of the digestive menu of humans, researchers measure the wealth in different eras and civilizations by the purchasing power of daily wage to buy wheat. The concept of the "wheat wage" [International Institute of Social History (IISH), 2021] offers a unique perspective on measuring wealth across various epochs and civilizations. Given that wheat serves as a fundamental component in the human diet, researchers use the purchasing power of wheat, determined by a daily wage, as a yardstick for evaluating economic prosperity. This approach, as documented by scholars such as van Wees (2006), Scheidel (2010), Milanovic et al. (2007), Jursa (2010), Loomis (1998), Milanovic (2006), Van Zanden (1999), Malanima (2013), and Sargentis et al. (2022a,d), provides a consistent and tangible measure that transcends the fluctuations in the values of money and precious metals. By anchoring economic comparisons to a staple commodity like wheat, which has been a dietary staple throughout history, the "wheat wage" method enables a more reliable assessment of the relative economic wellbeing of societies across different time periods.

The stability of the wheat wage as a metric allows for a more meaningful and robust comparison of economic conditions. Unlike currencies or precious metals, the consistent presence and importance of wheat in the human diet provide a constant reference point. This method not only facilitates cross-temporal comparisons but also sheds light on the tangible and essential aspects of economic wellbeing, emphasizing the centrality of food in gauging the wealth and living standards of diverse societies throughout history.

In order to produce wheat for a family, a villager needed *ca.* 179 working days in the 1950s. With this work, he gained on average 8.7 kg/day (or $8.7 \times 1.29 = 11.22$ L/day). Considering that the average wheat wages in antiquity were 6.12 kg/d or 7.9 L/d, which was close to what we considered as the limit of extreme poverty (World Bank, 2015; Ravallion (1992) and Rohwerder (2016) (5 kg or 6.5 L of wheat wage in 2015), Sargentis et al. (2022a,d) and Rohwerder (2016) noted that the living standards of inhabitants in the 1950s were close to this limit (depicted in Figure 9A with a red dashed line). In order to compare it with the present, we note that the average wage in Greece (2021) was €54.32, which was equivalent to approximately 150–200 kg or 195–260 L of wheat (depicted in Figure 9A with a red dashed line).

It is reported that wheat cultivation in the 1950s was not for trading but for covering their own needs. The expected daily quantity for a person in a family of 6 members was 0.5 kg or 0.9 L (2.45 kcal), which could cover the survival caloric needs (1.8–3 kcal/day) [International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD), 2009; Berners-Lee et al., 2018; Nestle and Nesheim, 2012]. According to the Dietary Guidelines for Americans, the recommended daily intake of grains for most adults is approximately 170 to 227 g of grains per day (USDA, 2020). In a normal year, the wheat could give a surplus, which would be used in the exchange economy, but in a bad year, the wheat was marginal for survival (Figure 9B).

The cultivation process of wheat was not profitable in 2023 as the price of wheat was very low in the local market (0.22 €/kg), and the earnings were lower than the cost of production even if 2023 was a year with a production close to the average (Figure 9C). At the same time (July 2023), the inflation in Greece was 2.5%, and the inflation in food (Euro2day, 2023; Tsiros, 2023) was 12.3%.

Due to the complexities and challenges associated with assessing the dynamics of land, taking into account factors such as weather conditions, unpredictable events (wild boars that attack the crops, diseases, insects, and natural disasters), and the inherent inequalities in the cultivation process (even within a confined area), the outcomes vary widely. As a result, the quantification of these variables is acknowledged to be feasible only on an order of magnitude basis, emphasizing the inherent uncertainties and variabilities in agricultural outcomes.

The comparison of the WEF nexus between the 1950s and 2020s using average values is depicted in Figure 10. The choice of average values implies an effort to capture general trends rather than precise measurements, aligning with the earlier acknowledgment of the challenges associated with quantification due to the multifaceted nature of agricultural dynamics.

The diagrams within Figure 10 present a quantitative comparison between the 1950s and the 2020s, encompassing the following aspects: the capacity of farmers to feed people, the quantity of available

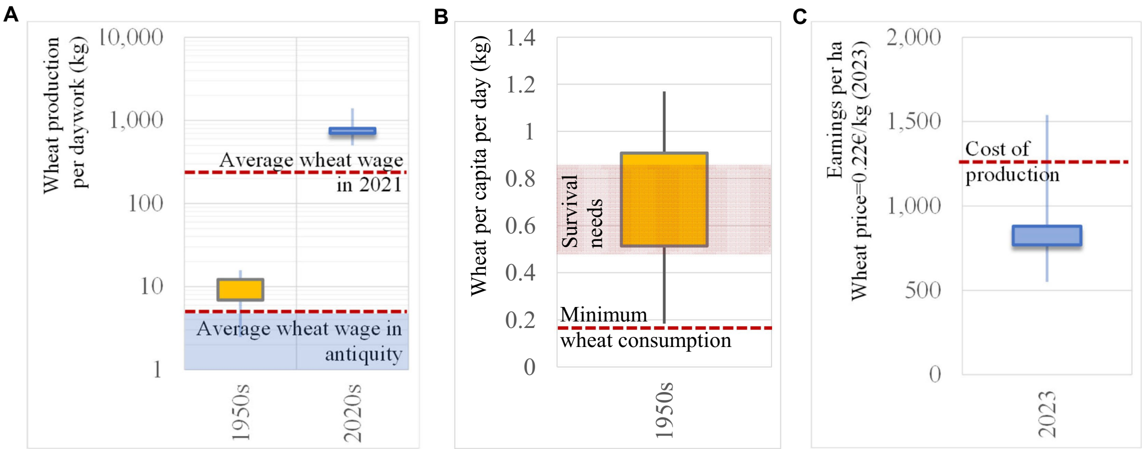

FIGURE 9
(A) Wheat wages and wheat production per daywork; **(B)** wheat *per capita* per day in Kerinthos (1950); **(C)** financial analysis in market values (2023).

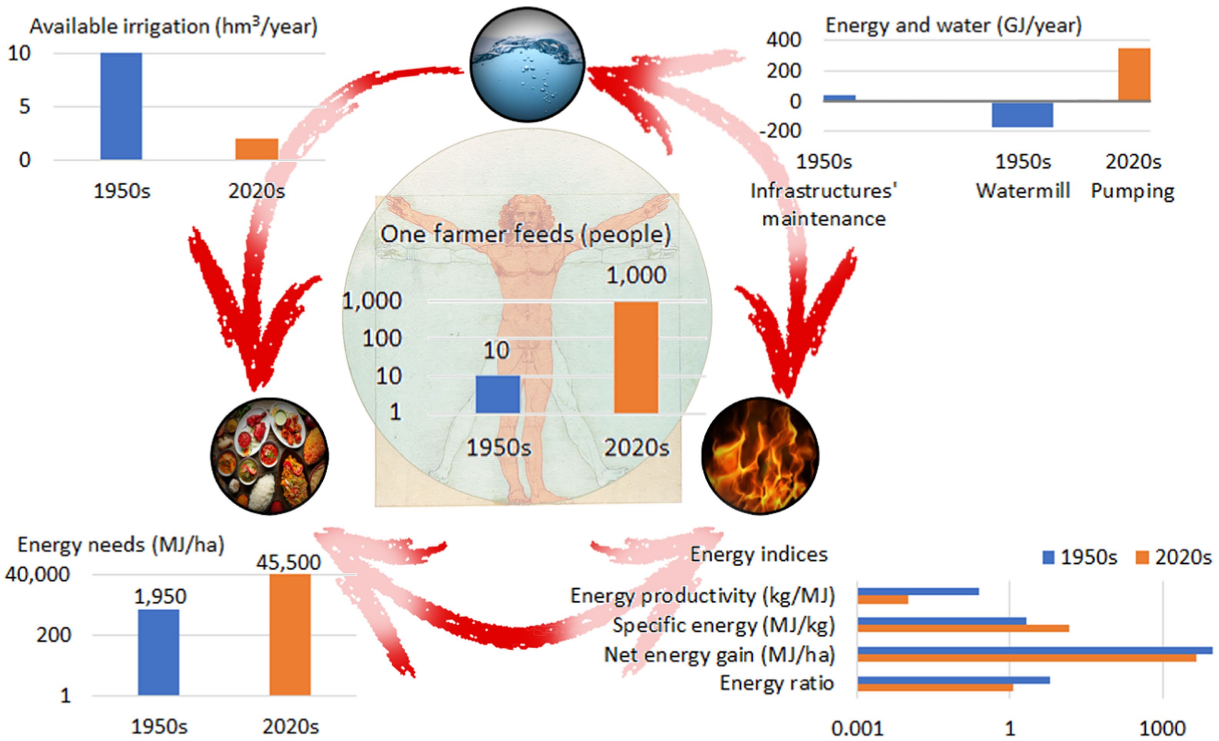

FIGURE 10
Function with average values estimated by the calculations of this study in order of magnitude (barren areas) of the WEF nexus in village Kerinthos in the 1950s and 2020s.

irrigation water, the energy sources utilized for water and the corresponding energy generation (in the 1950s), the energy requirements for cultivating a hectare, and the energy indices.

6 Policy implications

The comprehensive discourse on the nexus is molded by diverse societal spheres and the considerable impact of development stakeholders. Consequently, a substantial portion of the nexus literature comprises policy reports, position papers, working papers, or strategy documents produced by international agencies, national ministries, consultancies, transdisciplinary networks, or financial institutions. With the growing prominence of the WEF nexus debate, it increasingly shapes international development and resource governance strategies (Beddington, 2010; Wiegleb and Bruns, 2018).

Kerinthos in the 1950s fed approximately 500 people with a small surplus for trading, but even kids worked in agriculture to support their survival needs. Today, the village has almost the same population as in the 1950s, but only 20—30 people are employed in agriculture. Considering barren areas (254 ha) cultivated with wheat, in a normal year (on average 3,750 kg per ha), the production will be *ca.* 1,100 tons of wheat. This wheat could feed 10,500 people annually with 50 dayworks per year by each farmer. Adding the production of the fertile areas (295 ha), Kerinthos' plain could cover the wheat needs of approximately 30,000 people [approximately 1% of the population of Athens (Sargentis et al., 2019), who live in approximately 300 ha (Athens' population density 10,446 capita/km^2)] (Ballas, 2022).

With modern farming methods, one farmer in Kerinthos could feed 1,000 people. As the cultivation process is not in the state of the art and estates are scattered, this process could be more efficient in other areas. It is noted that this evolution of agricultural practices gave the abilities of the evolution of human clustering in cities (Sargentis et al., 2020b, Mamassis et al., 2021), which are not self-sufficient (Schulterbrandt Gragg et al., 2018). However, as wheat prices vary in the market, the cultivation process of wheat was not financially profitable for farmers in 2023 (Figure 8C).

Extreme events in the summer of 2023, such as the end of the grain deal (BBC News, 2023; Wintour, 2023) and the rice ban by India (Biswas, 2023), could trigger a global food crisis. Among this series of unfortunate events, we must also include the catastrophic flooding caused by the extreme rainfall event named "Daniel" from September 5, 2023 to September 22, 2023, as documented by Copernicus (Copernicus Emergency Management Service, 2023). This flood resulted in a catastrophe in the Thessaly Plain, the primary source of food supply in Greece, inundating an extensive area of 72,000 ha (Kalaitzi, 2023).

The situation is paradoxical as the financial abandonment of farmers, crucial for supporting food security, is happening simultaneously with unstable food supply chains (Guterres, 2022; International Monetary Fund, 2022; United Nations, 2022) and rising prices. Noting that this does not happen at the local scale, it seems that this is a wider "Global War on Farming" (Vlaardingerbroek, 2023), which forms a global conflict with profound consequences. In this frame, the abandonment of farmers by European elites triggered unrest among farmers in Europe in the winter of 2024 (De La Hamaide and Trompiz, 2024), posing a new threat to social cohesion.

A rational view of the concept of the WEF nexus should not surprise anyone (Sargentis et al., 2022a,d). As the energy prices have risen since the Russian–Ukrainian military conflict (Henley, 2024) and the modern production of food is an energy-intensive process (fuels and fertilizers), it is obvious that farmers would be in trouble sooner or later. However, it is not only a farmers' trouble, because one farmer feeds a lot of citizens, as documented above, but also a vital problem for people who live in cities.

Jeopardizing the livelihoods of those in agriculture contradicts efforts to ensure food security, especially with unpredictable challenges to supply chains. In addition, the increased energy and food costs highlight the need to reconsider such practices. A more comprehensive approach is to reconsider that the fundamentals of a thriving society are not the abundance of money but the abundance of water, energy, and food (Sargentis and Koutsoyiannis, 2023).

7 Conclusion

Greek province was in a preindustrial era until the 1950s and modern practices have been adopted thereafter.

In the 1950s, one day work of a villager could provide food for *ca.* 10 people, but as the range of production varies, in some periods, these quantities could be marginal for survival (Figure 8B). Correlating the quantities with wheat wages, the villagers in the 1950s were living marginally above the limits of extreme poverty (Figure 8A). Considering the above fact, prior to the consolidation in the 1930s, villagers were relinquishing half of the production to the landowner, it can be concluded that the living standards before the 1930s were unquestionably lower than the thresholds of extreme poverty (Koutsoyiannis and Sargentis, 2021).

The goal of modern practices to provide more food with less work on the same land has been achieved by the abundance of energy. Consequently, this trend contributes to an increasing degree of urbanization worldwide. However, the WEF nexus does not appear to be optimized. This is indicated by the energy indices and the water management, as nowadays farmers prefer pumping from aquifers which consumes a considerable amount of energy for smaller quantities of water, in contrast to the previous era with the abundance of water which came by irrigation channels from the river (and also gave energy to watermill) (Figure 10).

Furthermore, even if farmers are the foundation of both traditional and modern ways of living, and supply chains in 2023 have become destabilized, their work in 2023 was not profitable.

Given that the research referred to the 1950s and relied on the description and recollection of an interviewee who was born in 1938, it is notable to highlight the significance of the memories of elderly people. As this process opened a hidden library, the quantitative analysis of these descriptions gave us the necessary inputs to estimate the human progress of the management of the WEF nexus in the last century in Greece. This intentional focus aims to shed light on the rich tapestry of experiences held by seniors, highlighting their unique contributions to a more comprehensive understanding of various aspects, be it cultural heritage, societal shifts, or historical events.

Further research could use the same methodology to examine WEF and land nexus in other areas of Greek province with different anaglyph, hydrological characteristics, and dynamics of the WEF nexus, in the same time periods.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

G-FS: Conceptualization, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing.

NM: Validation, Writing – review & editing. OK: Writing – review & editing. DK: Validation, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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