Article

Solutions of Minimized Agrochemicals Input in the Post Zero-Growth Era: A State-of-the-Art Analysis of the Hengduan Mountains, China

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ABSTRACT: How to further reduce the input of agrochemicals after zero-growth is an important challenge faced by mountainous areas. Up to now, the combined solution for minimized agrochemicals intervention in the post zero-growth era has not been systematically analyzed globally. Here, the Hengduan Mountain regions (HMR) in China, as a case, we estimated the turning points of agrochemicals input intensities using a quadratic equation, as well as integrating policy document analysis and literature review. Results show that the occurred timeline of fertilizer and pesticide use zero-growth in 10 municipalities (prefectures) in the HMR is relatively wide, with a distribution from 2009 to 2019, illustrating that all municipalities (prefectures) have been achieved national goals ahead of 2020 deadline. Thus, the incentive of a series of national-level policies focusing on chemical fertilizers and pesticides has proven effective in achieving the zero-growth target of agrochemicals input in the HMR. However, comparison with major mountainous countries like Germany, Italy, Portugal, Romania, Austria, and Spain *etc*., there are clearly many opportunities for enhancement in reducing fertilizer and pesticide uses. We present a practical route to minimize agrochemicals application in the HMR through crop rotation-based agro-biodiversity solutions, organic alternative-based soil health solutions, professionalization-based precision farming solutions, smallholder farmers' awareness-based behavior intervention solutions, conservation reserve-based zoning solutions, *etc*.

Keywords: Fertilizers; Pesticides; Zero-growth; Hengduan Mountain Regions; Policy analysis

1. Introduction

Most of the global studies about agrochemicals inputs are principally focused on fertilizers and pesticides [1]. To feed the rapidly increasing world population, over the past few decades, as an essential element of contemporary agriculture and a major option for addressing sustaining food production, chemical fertilizers and pesticides have significant contributed to enhancing crop output, increasing income of farmers and ensuring national food security [2–5]. In particular, in most developing countries, researchers and policymakers widely recognized that increasing inputs of both chemical fertilizers and pesticides is a vital means to raise agricultural productivity and crop yield [3,6,7]. Similar evidence exists even in developed countries, which also prefer to use more inputs such as fertilizers and pesticides [8]. Importantly, the heterogeneity of different farms, crops and regions is highly apparent [9–11]. Ahvo et al., who, used a random forest machine learning algorithm to model the effects of agricultural input shocks on crop yields, found that shocks in the input of fertilizers and pesticides could cause drastic yield losses [12]. Buttinelli et al., in turn, use an agro-economic supply model to investigate the impacts of chemical reduction on maize grain production [13]. They argued that reducing chemical inputs may lead to declines in agricultural production, income, and added value. Similarly, Wesseler estimated a decline in EU agricultural output due to the "farm to fork" (F2F) strategy [14],

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while Barreiro-Hurle et al., identified that agricultural output volumes were projected to fall by 7–12%, further resulting in greater EU dependence on imported food [15]. This theoretically and practically illustrates why farmers tend to input as much as possible fertilizers and pesticides to raise agricultural production [2].

A large body of literature has investigated the threshold effect of fertilizer and pesticide inputs, and ways of minimization them, for example, agri-cooperative organization, farmland transfer, management practices, precision control system, economic incentives and regulatory restriction, stakeholder trade-offs *etc*. Representative authors from different regions in the world include Cheng et al. [6], Brunelle et al. [16], Li et al. [17], Yin and Cui. [18], Jacquet et al. [19], Liu and Wu [20], Tian et al. [4], Zanin et al. [21], Yang et al. [22], and Xie et al. [23] *etc*. Lechenet et al., using data from 946 non-organic arable commercial farms, found that pesticide usage could be reduced by 42% without any negative impacts on agricultural yields and earnings in 59% of French farms [24]. Peng et al., employing multiple regression models with provincial-level balanced panel data from China, estimated that the level of farmland transfer rises by 10%, fertilizer usage reduces by 3.30%, while pesticide decreases by 3.62% [25]. Moreover, the application rates of chemical fertilizer and pesticide vary with the average age, education level and environmental awareness of farmers [26]. However, chemical fertilizers and pesticides are like a double-edged sword. The most recent studies indicate that the prolonged and excessive use of chemical fertilizers and pesticides not only poses a tremendous threat to environmental health, such as agricultural non-point source pollution, heavy metal pollution, biological deterioration of the soil, and biodiversity loss, but it also induces higher risks in achieving agricultural sustainability [4,27–31]. Undoubtedly, despite widespread improved crop yields by using pesticides and chemical fertilizers, global agrifood systems today face a raising crisis triggered by contaminated food and the environment [32,33]. The reduction of chemical fertilizers and pesticides, as a key driving force for protecting human health and the environment and a policy focus for avoiding adverse human health and environmental impacts, has received widespread attention from scientists and policymakers [19,24,34]. The European Union has forged an international role in this regard. In 2009, the framework directive (2009/128/EC) provided a range of actions to implement the Integrated Pesticide Management Strategy (IPM), which promotes the environmentally friendly alternatives to chemical pesticides and the development of organic agriculture [35]. To balance agricultural needs with environmental protections, even though the European Commission has abandoned targets set out in legislation to cut pesticide and fertilizer use by 50% by 2030, lowering reliance on chemical fertilizers and pesticides, as a major pillar of the European Green Deal and "farm to fork" (F2F) strategy, is always a priority in European agricultural policies [10,36]. Actually, numerous studies have demonstrated the positive effects of replacing or reducing chemical fertilizers and pesticides with organic fertilizers and bio-pesticides on sustainable agriculture practices [33,37]. As Krause et al.' study, organic and green cropping systems, as a promising approach and practice to achieving harmony between agricultural activities and the environment, could enhance soil health, boost soil biodiversity, and higher yields were also achieved [38]. Ensuring food safety is essential for better health and improved well-being [39].

China, as the world's largest agricultural producer by volume and the world's second-largest agricultural importer by value, a total cumulative quantity of pesticides and fertilizers for the period 2000–2022 reached 35.45 million tons and 1030.49 million tons, respectively. This has led to widespread environmental impacts [2,6,17,25,26,31,40]. To reduce the burden of synthetic fertilizers and pesticides on the environment, producing sufficient, safe, and environmentally friendly food without adverse environmental impacts is the ambition of achieving the sustainability of agroecosystem in China [31,41–43]. Against this background, an important strategy for reducing pesticide and fertilizer inputs in agriculture is currently gaining momentum in China [6,18,40]. Since 2015, the Ministry of Agriculture and Rural Affairs (MARA) has issued the Action Plan for Zero Growth in Fertilizer and Pesticide Use by 2020. As a result, the use of pesticides and fertilizers declined rapidly, reaching 1.25 and 50.79 million tons respectively in 2022. The intensity of pesticide and fertilizer application also declined to 7.4 and 298.8 kg per hectare of cropland, respectively, in 2022. However, compared to developed countries (especially US and EU nations), the use and application intensity are still high [44–46]. Due to the climatic and topographic complexity in China, crop species diversity results in large spatial variability of the intensity of pesticide and fertilizer inputs [6,25,47,48]. There have been numerous studies carried out on pesticide and fertilizer use and their environmental effects around the world, but almost all have focused on lowland areas. It should be noted that the extent of the mountainous region accounts for 74.9% of Mainland China's total area [49]. With a few exceptions like Dhakal et al. [50], Wu et al. [51], Tan et al. [26], Zhang et al. [52], and Lamers et al. [53], there have been no attempts to underscore various aspects of reducing pesticides and fertilizers input in mountainous areas. Mountain specificities are characterized by both constraining features (such as accessibility, marginality, and fragility) and enabling features (for instance, diversity, niche, and human adaptive capacity) [54]. Indeed, vulnerability in mountain systems is likely to be exacerbated by excessive or inappropriate use of chemical fertilizers and pesticides. Therefore, understanding the use dynamics of agrochemicals as well as corresponding strategical course for mountainous regions throughout China is an important pathway towards meeting multiple goals of reducing usage, conserving natural resources, and enhancing the well-being of farmers.

This article addresses the dynamics of chemical fertilizers and pesticides input in western mountainous regions of China, and aligns with the national schedule of fertilizer and pesticide reduction. We aim to shed light on the trend of fertilizers and pesticide inputs, to give explanations as to why this is happening, to analyze the inflection points of fertilizer and pesticide zero-growth, and to compare the evolution gaps of fertilizer and pesticide use intensity between mountainous regions and the whole nation. Specifically, it is crucial to acknowledge that agrochemicals input varies significantly across different regions and different geographical scales. As such, the endeavor to reduce their usage and intensity depends on the unique regional context. We suggest potential strategies for defending a healthier way of life, further lowering agrochemical intervention when China's mountainous areas transition to the post zero-growth era. The article is organized as follows: Section 2 presents research methodology. Section 3 discusses the estimated zero-growth timeline of both fertilizer and pesticide input intensities, their regional differentiation, and key solutions to reducing agrochemical intervention in the context of post zero-growth era. Section 4 summarizes major conclusions.

2. Methods

2.1. Case-Study Selection and Its Basic Features

To illustrate the zero-growth timeline of chemical fertilizer and pesticide input in agriculture, the research focuses on the Hengduan Mountain Region of western China (HMR), with active tectonics, steep topography, varying exposure to the monsoon, and a subtropical latitude. Several features of this case study include: (i) the HMR, located in the southeast margin of the Qinghai-Tibet Plateau, is both transition zones from the first to the second tiers of China's terrain, and between subtropical and alpine regions (Figure 1). The combination of high mountains (such as Minshan, Qionglai, Dajinshan, Shaluli, Mangkang-Yunling, Tanian-Taweng-Nushan, and Boshula-Gaoligong), canyons, and a chain of approximately parallel rivers from north to south (*i.e.*, Minjiang, Dadu, Yalong, Jinsha, Lancang, and Nujiang Rivers, *etc*.) highlights the complexities of ecosystems. As an important ecological shelter zone in the upper reaches of the Yangtze River, this region plays a crucial role in conserving ecosystems [55–57]. (ii) owing to synergistic effects of terrain, high-altitude westerly wind, the Indian Ocean and Pacific monsoon on diverse habitats, the HMR is one of the world's 35 biodiversity hotspots, with winter dry and summer wet, diverse vertical structure of climate types, a large area of dry-hot valleys, and significant vegetation differences between slope aspects [58–61]. (iii) The interactions between the Asia-Europe with Indian and Pacific Plates create most of the geological drama, in conjunction with the process of heavy precipitation and severe convective weather, different types of geological disasters such as landslides, avalanches, debris flows, with a high incidence [62,63]. (iv) there are 10 administrative municipalities (autonomous prefectures) in this study area, including Nujiang Lisu Autonomous Prefecture, Diqing Tibetan Autonomous Prefecture, Dali Bai Autonomous Prefecture, Lijiang municipality, Chuxiong Yi Autonomous Prefecture in Yunnan Province; and Ganzi Tibetan Autonomous Prefecture, Aba Tibetan Autonomous Prefecture, Liangshan Yi Autonomous Prefecture, Panzhihua municipality and Ya'an municipality in Sichuan Province, with a total area of 438,800 square kilometers. A cluster of deep valleys surrounded by a series of tall mountains leads to a limited area of fat arable land, which is mainly the livelihood capital that rural residents depend on. Human-land conflict represents a significant and growing challenge in ecosystems conservation and agricultural sustainable development [56,64]. (v) the HMR' population stood at more than 17.57 million as of 2022, with a rural rate of 55.4%, which is higher than the national average of 34.8% during the same period. The share of GDP from agriculture was over 18%, 10.7 percentage points higher than the national average for the same period. For this reason, strong dependence on agriculture and rural livelihoods is closely linked to climate change and the environment. Therefore, natural disasters include all types of severe weather that have the potential to pose a significant threat to agriculture and rural livelihoods such as agricultural product prices, household income and livelihood options *etc*. [56,65,66]. (vi) due to the relatively unfavorable geographic location and historical foundation, the per capita GDP in the HMR was only roughly 65% of the national average in 2022. The per capita disposable income of rural residents in the HMR was approximately CNY 16,882 (roughly $2325), while the nationwide per capita disposable income of rural residents was CNY 20,133 (about $2775), widening an absolute income gap of CNY 3251. In addition, the HMR is a multiethnic region inhabited by over 40 minority ethnic groups, including Yi, Tibetan, Bai, Lisu, Qiang, Naxi, Nu, Dulong, Pumi, Hui, and Miao, *etc*. Among them, the Yi, Tibetan, Bai, Lisu, Qiang, and Naxi ethnic groups account for 25.5%, 9.2%, 8.3%, 3.2%, 2.5%, and 1.6% of the total population, respectively.

Figure 1. Map of study area (Note: The national boundaries involved in this map are produced based on the standard map with the map review number GS (2020) 4630, which was downloaded from the Standard Map Service website of the Ministry of Natural Resources of the People's Republic of China (http://bzdt.ch.mnr.gov.cn/, accessed on 19 July 2025). The base map remains unmodified).

2.2. Key Metrics

Although the inputs of both chemical fertilizer and pesticide in absolute terms have been dropping, this is not necessarily linked to a decrease in use intensity. To address the use intensity of fertilizers and pesticides in agriculture is crucial for improving food security and accelerating the overall green agricultural transformation [6,16,67–69].

Indicator of fertilizer use intensity: intensity of chemical fertilizer input in agriculture measures the mean amount of a given fertilizer input used per hectare of cropland (kg/ha). This indicator may assess the need to supply more, or in cases of overuse, explore targeted options to advise farmers about how to reduce the fertilizer amounts used or use the fertilizer more efficiently at national, regional, and local scales.

Indicator of pesticide use intensity: similar to fertilizer, intensity of pesticide use refers to the average amount of a given pesticide input used per hectare of cropland (kg/ha). The intensity of pesticide use in agriculture can compare the spatial-temporal heterogeneity at various spatial scales, and also can provide basal data for decision-making in managing food production and environmental impact assessments.

2.3. Diagnosis for Zero-Growth Turning Point

In order to estimate the zero-growth inflection point of both fertilizer and pesticide inputs, this paper employs a quadratic equation, with time-series (year) as the *x*-axis and the intensity of fertilizer and pesticide use as the *y*-axis, simulating y change over time x. The graph of a quadratic function is a U-shaped curve called a parabola. One important feature of the graph is that it has an extreme point, called the vertex. Namely, the vertex is a turning point on the graph. If the quadratic has a negative leading coefficient (a), the vertex represents the maximum value (turning point) for the area. The general form of a quadratic function presents the function in the form:

$$f(x) = ax^2 + bx + c$$

where a, b, and c are real numbers and $a \neq 0$. If $a > 0$, the parabola opens upward. In contrast, if $a < 0$, the parabola opens downward. The x-coordinate of the vertex is found using $x = -b/2a$. Once we have this x-value, we can substitute it back into the function to find the y-coordinate of the vertex, completing the turning point (x_{t1}, y_{t1}).

2.4. Data Sources and Time Scale

Data collection principles: adhering to the principles of integrity, credibility, continuity, accessibility, and comparability of statistical data, 10 municipalities (prefectures) in the HMR are selected as the study sample to ensure the consistency of administrative records data with the quality of a set of statistical data. The DEM data were sourced from the Geospatial Data Cloud platform (www.gscloud.cn, accessed on 19 July 2025), with a resolution of 30 m.

Major mountainous countries include: Andes (Bolivia, Ecuador, Peru, Colombia); Asia (China, Japan); Alpes (Bulgaria, Romania, Greece, Spain, Poland, Portugal, Italy, Slovakia, Slovenia, France, Austria, Germany, Switzerland); Highlands of western Europe (Ireland, United Kingdom); Scandinavia Peninsula (Finland, Norway, Sweden).

Data extracted directly from the official sources and non-profit organization for the University of Oxford: (i) the statistical yearbook from the annual Yunnan Statistical Yearbook, Sichuan Statistical Yearbook, Sichuan Agricultural Statistical Yearbook, Sichuan Rural Statistical Yearbook, Sichuan Survey Yearbook, as well as statistical yearbooks of various administrative municipalities (prefectures). (ii) China Statistical Yearbook. (iii) The statistical bulletin from various administrative municipalities (prefectures) and the Third National Land Survey, released jointly by the State Council, the Ministry of Natural Resources, and the National Bureau of Statistics. And (vi) the data on fertilizers and pesticides use in major mountainous countries comes from Our World in Data at the University of Oxford [46].

Periodicity in time series data: In this article, statistical data covering the period from 2000 to 2022 is employed to display the evolution trajectory, curve changes, and spatial differences of chemical fertilizer and pesticide inputs in agriculture. The intensity data of agrochemicals use in major mountainous countries is from 2021.

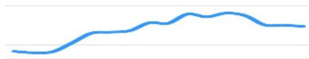
3. Results and Discussion

Agriculture in the HMR has developed rapidly since 2000. In 2022, the total grain output of the entire region was 7.348 million tons, the value-added agriculture was CNY 178.38 billion, and the per capita disposable income of rural residents was CNY 16,882, an increase of 1.21, 8.9, and 11.5 times compared with that of 2000, respectively. However, at the same time, the cumulative inputs of fertilizer and pesticide in the HMR from 2000–2022 is 12.916 million tons and 285.4 tons, respectively. Considering the negative impact of fertilizers and pesticides on the environment and human health, China's central government, in collaboration with the Ministry of Agriculture and Rural Affairs, has adopted a strategy for controlling fertilizers and pesticides use and improving agricultural productivity, and adapting to green evolution of agriculture since 2000, and seeking to achieve zero-growth in input of fertilizers and pesticides by 2020. As a result of the wide disparity in agricultural production conditions and uneven levels of development, the process towards achieving the goal of zero-growth in use of chemical fertilizers and pesticides presents an inconsistent step across the HMR.

3.1. Intra-Regional Gaps in Zero-Growth of Fertilizers Input for the HMR

Statistical results display that the intensity of fertilizer use per hectare of cropland through running a nonlinear simulation in Excell, all 10 municipalities (prefectures) in the HMR meet the quadratic function condition, and the goodness of fit using R-squared is above 0.5500 (Table 1). This critical value of R^2 indicates that the quadratic function is sufficient for describing the data, illustrating a strong explanatory power in understanding the relationship between the independent (time variable, x) and the dependent variable (the intensity of fertilizer input, y). In terms of when inflection point occurred, Panzhihua in Sichuan Province was the area where the intensity of fertilizer use first showed a turning point on the graph, while Ya'an occurred relatively late. The progress chart in achieving zero-growth targets in 10 municipalities (prefectures) is as follows: Panzhihua (2009), Dali and Liangshan (2011), Chuxiong (2012), Ganzi (2013), Lijiang and Aba (2014), Nujiang and Diqing (2018), Ya'an (2019).

Table 1. Regional variations in fertilizer usage per hectare of cropland in the HMR.

Administrative Region Name		Simulated Function	Goodness of Fit (R^2)	Estimated Turning Point	Dynamic Curve
Yunnan Province	Nujiang	$y = -0.4229x^2 + 10.087x + 37.33$	0.8540	2018	
	Diqing	$y = -1.3539x^2 + 31.693x + 65.24$	0.9091	2018	
	Lijiang	$y = -1.1719x^2 + 35.621x + 209.24$	0.9652	2014	
	Dali	$y = -1.7302x^2 + 39.857x + 204.05$	0.8272	2011	
	Chuxiong	$y = -0.5791x^2 + 15.248x + 271.82$	0.5128	2012	
Sichuan Province	Aba	$y = -0.5058x^2 + 14.752x + 56.11$	0.7227	2014	
	Ganzi	$y = -0.1219x^2 + 3.4022x + 15.22$	0.8200	2013	
	Liangshan	$y = -0.3062x^2 + 7.3749x + 149.40$	0.5524	2011	
	Panzhihua	$y = -1.1802x^2 + 23.095x + 354.95$	0.8636	2009	
	Ya'an	$y = -0.6497x^2 + 25.866x + 148.69$	0.7489	2019	

The reason why the fertilizer application density in Panzhihua municipality and Liangshan Yi Autonomous Prefecture climbed the zero-growth inflection point ahead of other municipalities (prefectures) may be closely related to the fact that Sichuan Province focuses on a range of promoting green agriculture practices and pilot demonstrations. In the early 1990s, recognizing the critical role and positive impact of green agricultural products in the food market chain, Sichuan developed green food in sync with the rest of the country through the use of production and marketing contracts to enhance competitive capacity and security over the past three decades, and the philosophy of reducing fertilizer usage gradually was penetrated. Subsequently, the province's ongoing "promotion, adjustment, transformation, substitution, and pilot" campaign has had a substantial impact on fertilizer reduction. Specifically, the persistent emphasis on reducing fertilizer has been driven by differential experiences such as popularizing technological adoption of fertilization application through soil testing and formula fertilization (promotion); adjusting the structure of fertilization inputs with the creation of standard parks for horticultural crops (adjustment); transforming utilization ways of fertilization with the control system of water-fertilizer integration (transformation); partially replacing chemical fertilizers with animal-sourced organic fertilizer, especially composted manure (substitution); implementing pilot initiative of reducing fertilizer usage and increasing efficiency through hub construction of the South-to-North Vegetable Transport Project (pilot). Because of unique topography and climatic conditions, Anning River Basin in the western part of Sichuan, as the second largest plain in Sichuan and known as the second granary of Tianfu, is a crucial agricultural production base such as commercial vegetables, tropical fruits and cereals. As a consequence of this, Liangshan and Panzhihua have been very central to reducing fertilizer use, conducting field experiments for important crop species, and demonstrating green agricultural development in Sichuan Province.

The early occurrence of an inflection point in Dali may be attributed to numerous government strategies for addressing lake catchment ecological restoration and water quality protection in the Erhai Lake, which is located in Dali, and is the second largest highland freshwater lake in Yunnan Province. As early as 2006, the State Council of China approved a Special Program for Erhai Lake's Water Pollution Control and Treatment. This program clarified the widespread sources and major solutions of rural non-point source pollution from pesticides, fertilizers, and animal manure *etc*. The corresponding actions, such as optimizing planting structure, managing livestock and poultry manure effectively, promoting organic fertilizer substitution, controlling pest and disease by combing ecological tools, promoting the healthy development of aquaculture, and transforming tourism for realizing the potential of sustainable tourism, were likely to capture the potential root causes that are identified in the program. Still, at the regional level, the increased intensity of applying innovative financing mechanisms, strengthening institutional and governance arrangements, and building the skills and capacity of lake management authorities, in combination with strong local community engagement to underpin long-term management actions, may have affected fertilizer reduction in the entire Erhai catchments. The total fertilizer consumption stood at nearly 95,500 tons in 2022, which is equivalent to 51.2% of the peak year.

3.2. Intra-Regional Gaps in Zero-Growth of Pesticides Input for the HMR

Similar to fertilizers, based on the time-series data of pesticide use intensity from 2000 to 2022, we use Excel to simulate the interannual variability. Results indicate that, except for Liangshan, which fails to find statistical significance all the time, the other 9 municipalities (prefectures) in the study area all follow the standard form of quadratic function, and statistical goodness of fit (R^2) is all above 0.5400. Because all a-values are negative, the corresponding graphs open downward, with a maximum (inflection point) respectively (see Table 2). Modelling data further reveal that Ganzi in Sichuan Province was the earliest region to experience a turning point of pesticide input intensity, while Aba, Ya'an in Sichuan Province, and Nujiang in Yunnan Province experienced it relatively late. With respect to the zero-growth turning point of pesticide input intensity, the timeline charts in 9 municipalities (prefectures) were as follows: Ganzi (2010), Chuxiong (2011), Panzhihua (2012), Dali (2013), Lijiang and Diqing (2014), Nujiang, Aba, and Ya'an (2015) respectively.

Table 2. Regional variations in pesticide usage per hectare of cropland in the HMR.

Administrative Region Name		Simulated Function	Goodness of Fit (R^2)	Estimated Turning Point	Dynamic Curve
Yunnan Province	Nujiang	$y = -0.0183x^2 + 0.2431x + 0.519$	0.5463	2015	
	Diqing	$y = -0.0174x^2 + 0.5299x - 0.088$	0.5939	2014	
	Lijiang	$y = -0.0292x^2 + 0.7047x + 3.47$	0.6902	2014	
	Dali	$y = -0.0574x^2 + 0.6356x + 8.581$	0.7884	2013	
	Chuxiong	$y = -0.019x^2 + 0.4044x + 6.09$	0.5907	2011	
Sichuan Province	Aba	$y = -0.0156x^2 + 0.4607x + 3.4742$	0.5487	2015	
	Ganzi	$y = -0.016x^2 + 0.3584x + 0.7282$	0.8506	2010	
	Liangshan	---	---	---	
	Panzhihua	$y = -0.082x^2 + 2.1686x + 3.0781$	0.8467	2012	
	Ya'an	$y = -0.0487x^2 + 0.8878x + 3.6889$	0.7423	2015	

Zero-growth turning point of pesticide input intensity in Ganzi Tibetan Autonomous Prefecture faster than other municipalities (prefectures) may be due to the following reasons: firstly, the share of animal husbandry stood at around 55% of the total agricultural output value in 2022, and it is now increasing. This agricultural structure of pasture-based systems largely uses local natural renewable resources and relies less on pesticides compared to major crop-producing areas. At the same time, a lower proportion of farmland and farms can also dramatically result in lower pesticide usage. Secondly, Ganzi Prefecture is located in the mountainous region of western Sichuan. The 18 counties in Ganzi are known for their towering mountains, high average altitude, low annual temperature, and relatively weak incidences caused by pests and diseases. So, the low-flow concentration and intensity of pesticide consumption may be lower than those in other lowlands. Thirdly, the ethnic minorities in Ganzi Prefecture account for 87.8%. Most of them are Tibetan people, which accounts for 84.0%. Local herders in the region where grassland dominants, raise large numbers of domestic animals like horses, goats, and yaks, *etc*. All of these herders continue a long-standing tradition and practices of low-input/multiple output systems (transport, manure, milk, fiber, leather, meat) uniquely adapted to local climate variability. Natural pasture feeds the grazing livestock, which feed the soil with manure, urine, and treaded and dead plant parts, significantly lowering the use of pesticides across the Ganzi Prefecture. Chuxiong Prefecture is the hub of modern agriculture with distinctive features on the Yunnan Plateau, and is known as the "oasis of central Yunnan". In 2023, the extra-provincial trade of early winter vegetables in Chuxiong accounted for 60% of the entire Yunnan figure, making it an important logistics base for "transporting fresh vegetables from south to north" and "interprovincial vegetables trade". Since the early 1990s, the government of Chuxiong Prefecture has initiated a strategy, during the "the 8th Five-Year Plan" period (1991–1996), to vigorously develop green economies, especially green agriculture in all counties. In 2007, with green branding and positioning as a core value, the Chuxiong Fruit and Vegetable Association was established to promote the healthy development of green and high-quality agriculture. Local companies and farmers are leveraging sustainable practices to create a unique identity that resonates with the values of new generation consumers, who are concern about the environmental footprint and health of their purchases. In 2010, the government of Chuxiong Prefecture formulated the Food Safety Action and Special Rectification Work Plan to reduce chemical applications in agriculture. This initiative laid the foundation for improving pesticide management across the prefecture, accelerating the achievement of the zero-growth goal for pesticide input intensity, and enhancing the degree of green agricultural production.

3.3. Zero-Growth Gaps in Chemicals Input between HMR and the Country as a Whole

Our analysis shows that the pace of both fertilizer and pesticide reductions has a large intra-regional disparity, and the process of achieving the zero-growth target has diverged significantly. This assessment is undertaken with and without the impacts of both fertilizer and pesticide inputs on yields, to also assess the dynamics of reducing chemicals strategies at regional scale. To deepen understanding of the change in transformation of quantity into quality, to embrace sustainable practices for future agriculture, further identifying the entire HMR's inflection point for zero-growth at which it occurred and its actual position in national schedule, is also critical. Thus, the average intensity indicators of fertilizer and pesticide input as used here serve to estimate the timeline of the turning point that may arise from the dynamics captured in the entire HMR. As depicted in Figure 2, compared to the national schedule, the estimated turning point of zero-growth of fertilizer use in the entire HMR is consistent with national pace, both occurring in 2013, implying a period of increasing intensity of fertilizers use until 2013 and decreasing after 2013. Similarly, Figure 3 below presents the image of the intensity of pesticide use, showing that the turning point in the HMR lags behind the overall national process. The turning point of zero-growth in pesticide use intensity at national scale fell around 2011. The observation period from 2000 to 2011 was a period of growth in pesticide use, while the period from 2011 to 2022 entered a period of decline. Compared to the national average, the entire HMR is relatively 2 years behind, with the turning point occurring in 2013. This demonstrates the inherent relationships and disparities of chemical inputs in agriculture at various geographical scales; with different actors (regions) across zero-growth strategy domains having different performances of what the same policy action might be. Pesticide use intensity depends on many aspects, such as biological, agronomic, economic, and social factors. Heterogeneity between mountainous regions and the nation as a whole implies a potential and motivation for mountainous efficiency gains.

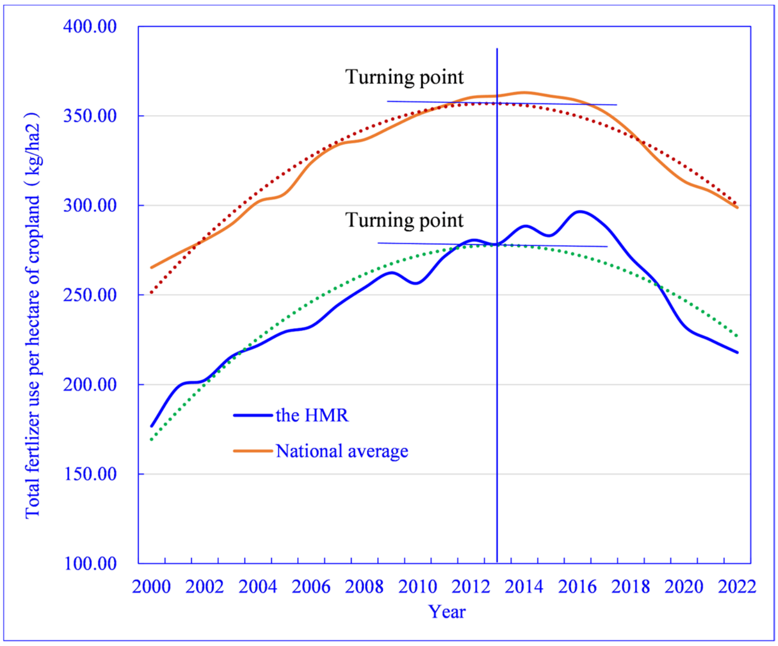


Figure 2. Dynamics of fertilizer input intensity and estimated turning point. Note: the solid line represents the actual observed values from 2000 to 2022, while the dashed line represents the simulated values based on quadratic equations.

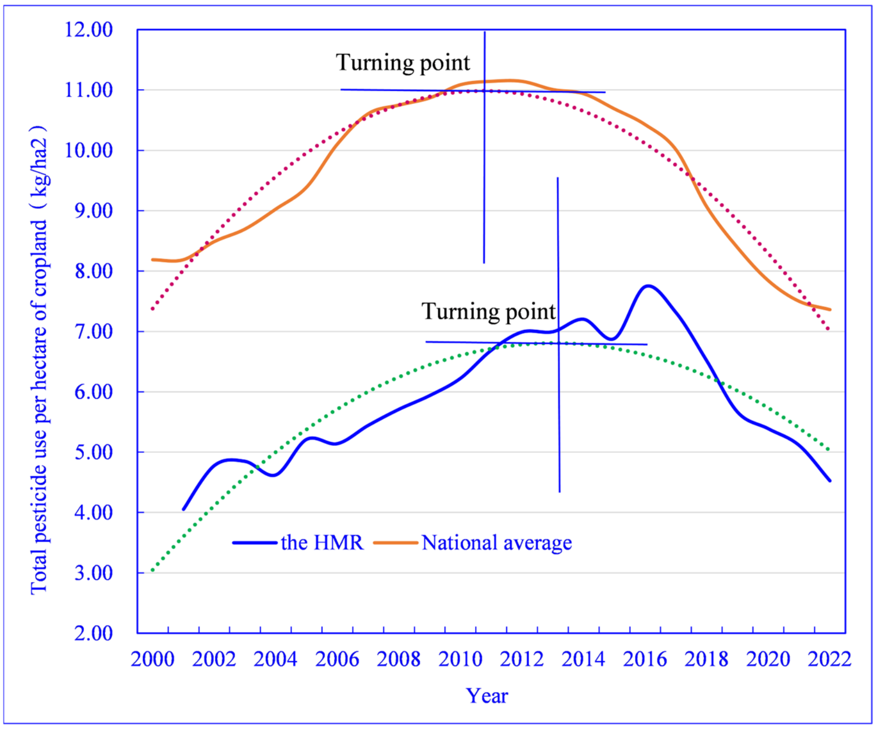


Figure 3. Dynamics of pesticide input intensity and estimated turning point. Note: the solid line represents the actual observed values from 2000 to 2022, while the dashed line represents the simulated values based on quadratic equations.

3.4. Driving Policies for Zero-Growth Target of Fertilizers and Pesticides

Since 2000, China has formulated a series of policies to regulate the usage of fertilizers and pesticides through addressing rationality, efficiency, and reduction pathways (Table 3). In particular, since 2015, the Ministry of Agriculture and Rural Affairs has unveiled the reduction strategies of fertilizers and pesticides, aligning with a nationwide zero-growth action, laying a solid foundation for the widespread adoption of agricultural green production. Among them, most of fertilizer and pesticide-related policies issued by China concentrated on the period from 2010 to 2019, with the number of policies accounting for 55% of the total statistics. In the highest single year (2015), six closely related policies were released (Figure 4). Although there are significant inter-annual and inter-regional differences in the progress of achieving zero-growth target of fertilizers and pesticides in various municipalities (prefectures) within the HMR, in general, like the whole country, the HMR achieved the expected target of zero-growth of fertilizers and pesticides set by the Ministry of Agriculture and Rural Affairs before 2020. According to data from the Ministry of Agriculture and Rural Affairs, the quality of the environment in agricultural production regions across the country has significantly improved. The coverage rate of green prevention and control of major crop diseases and pests has reached 54.1%, and the coverage rate of unified prevention and control of three major grain crops, such as rice, wheat, and corn, has reached 45.2% in 2023. The utilization rates of both fertilizers and pesticides have exceeded 41%. There is substantial evidence in various countries that national policy development and implementation an effective means of reducing chemicals input and environmental damage. As shown in Table 3, the performance of reducing fertilizer and pesticide use depends not only on the number of related policies issued by China, but also on aligning with targeted organizationl actions to drive efficient practices and success.

Table 3. Major reduction policies for fertilizer and pesticide use in China over the past two decades.

Revealed Time	Policy Scopes	Attention to the Use of Fertilizers and Pesticides
2024	● China's No.1 Central Document of 2024: Opinions of the CPC Central Committee and the State Council on Learning and Applying the Experience of the "Thousand Villages Demonstration, Ten Thousand Villages Improvement" Project to Forcefully and Effectively Promote Full Rural Vitalization.	To develop circular agriculture that balances planting and breeding, and focuses on using minimal amounts of external inputs such as chemical fertilizers and pesticides, closing nutrient loops, regenerating soils, and minimizing the impact on the environment.
2022	● Circular of the Ministry of Agriculture and Rural Affairs (MARA) on Issuing the Action Plan for Chemical Fertilizer Reduction by 2025 and the Action Plan for Chemical Pesticide Reduction by 2025.	By 2025, the share of organic fertilizers use will be increased by more than 5 percentage points; the intensity of pesticides used on rice, wheat, corn, and other major grain crops should be reduced by 5 percent compared with the 2016–2020 period.
	● Circular of the MARA, the National Development and Reform Commission (NDRC), the Ministry of Science and Technology, and other 8 departments on Issuing the "14th Five Year-Plan for the Development of the National Pesticide Industry".	To support the development of high-efficiency and low-risk chemical pesticides to meet the requirements of major pest control and pesticide-use reduction. To fully utilize synthetic biological technology to promote the innovation of traditional pesticides.
	● Circular of the Ministry of Ecology and Environment (MEE), the MARA, the Ministry of Housing and Urban-Rural Development, the Ministry of Water Resources, and the National Rural Revitalization Administration on Issuing the Action Plan for the Battle of Agricultural and Rural Pollution Control (2021–2025).	To establish exposure limits and license conditions through zoning and classification based on a total quantity control approach, to design eco-friendly and biocompatible alternatives for scientific, precise, and low-risk pesticide usage.
2021	● China's No.1 Central Document of 2021: Opinions of the CPC Central Committee and the State Council on Comprehensively Promoting Rural Revitalization and Accelerating Agricultural and Rural Modernization.	To continuously implement the action of using fewer chemical fertilizers and pesticides and increasing their efficiency, and to steadily enhance the level of green development in China's agricultural sector.
	● Opinions of the CPC Central Committee and the State Council on Further Fighting the Tough Battle of Pollution Prevention and Control.	Accomplishment of agrochemical input reduction and efficiency measures; In-depth implementation of the recycling action for agricultural films and introduction of a strict management system for agricultural films.
	● Notice of the State Council on Issuing the "14th Five-Year Plan for Promoting Agricultural and Rural Modernization".	The overall utilization rate of agrochemicals on three food crops is expected to reach the target of over 43% by 2025.
	● the 14th Five-Year Plan (2021–2025) for National Economic and Social Development and the Long-Range Objectives Through the Year 2035.	To promote sustainable transition focusing on agriculture's effects on nature and society, combining agroforestry with livestock farming offers opportunities for lower pesticide and fertilizers application.

	● Notice of the General Office of the MEE and the General Office of the MARA on jointly issuing the Trial Implementation Plan for Agricultural Nonpoint Source Pollution Control, Supervision, and Guidance.	To actively develop advanced waste recycling and chemical reducing technology in agriculture, and to introduce innovative policy and sound management for enabling agriculture's green transformative capacity.
	● Notice of the MARA, the NDRC, the Ministry of Science and Technology, and other 6 departments on jointly issuing the "14th Five-Year National Agriculture Green Development Plan".	Confronting non-point source pollution problem, improving the environmental quality of producing areas and agricultural ecosystems, by 2025, the green agriculture will be promoted in an all-round way.
2020	● China's No.1 Central Document of 2020: Opinions of the CPC Central Committee and the State Council on Doing a Good Job in the Key Areas of Agriculture, Rural Areas, and Farmers to Ensure the Building of a Moderately Prosperous Society in All Respects.	Managing livestock manure effectively from storage and treatment to application reduces the application of chemical fertilizers and pesticides, controls soil and water pollution, conserves arable farmland, *etc*.
2019	● China's No.1 Central Document of 2019: Several Opinions of the CPC Central Committee and the State Council on Prioritizing Development of Agriculture and Rural Areas to Address the Issues Relating to Agriculture, Rural Areas, and Rural People.	Shaping recycling habits and models, and launching campaigns to further reduce use of fertilizers and pesticides, and to ensure the quality and safety of agricultural products.
2018	● Notice of the MARA on Releasing the Technical Guidelines for Agricultural Green Development (2018–2030).	To accelerate the creation, production, demonstration, and commercialization of new technologies for reducing fertilizer and pesticide inputs and increasing efficiency.
	● China's No.1 Central Document of 2018: Opinions of the CPC Central Committee and the State Council on Implementing the Strategy of Rural Revitalization.	Prioritize the development of cleaner production, agricultural waste recycling, and ecological transformation of industries.
	● Opinions of the Ministry of Agriculture on Vigorously Implementing the Rural Revitalization Strategy and Accelerating the Transformation and Upgrading of Agriculture.	To perpetually reduce agricultural inputs and deeply execute zero-growth action of fertilizers and pesticides use.
2017	● The General Office of the CPC Central Committee and the General Office of the State Council jointly released the "Opinions on Innovating Institutional Mechanism to Promote Green Development of Agriculture".	To establish a sound system for reducing agricultural inputs and contrive zero-growth in the use of fertilizers and pesticides use.
	● China's No.1 Central Document of 2017: Several Opinions of the CPC Central Committee and the State Council on Deepening Agricultural Supply-side Structural Reform and Accelerating the Cultivation of New Driving Forces for Agricultural and Rural Development.	Deeply promoting the zero-growth action of chemicals, replacing chemical fertilizers with organic fertilizers, taking significant steps to cut expenses in agricultural inputs, and promoting cleaner production and maximizing the efficiency of agriculture.
	● Notice of the Ministry of Agriculture and eight other ministries and commissions jointly launching the Construction of the First Batch of National Experimental Demonstration Zones for Sustainable Agricultural Development to Carry out Early and Pilot Work on Agricultural Green Development.	This was the first policy on green development of agriculture released by China that focused on a green, circular, and low-carbon production system for agriculture, the target of zero-growth in the use of fertilizers and pesticides, and incentives for reducing agricultural non-point source pollution.
	● Circular of the MEE, the NDRC, and the Ministry of Water Resources on jointly printing and distributing the Water Pollution Prevention and Control Plan for Major River Basins (2016–2020).	Gradually controlling the input of chemical fertilizers and pesticides in the agricultural sector through the paths of precision, structural adjustment, and modification, achieving zero-growth, the goal of fertilizers and pesticides use for major crops across China by 2020.
2016	● Guiding Opinions of the NDRC, the Ministry of Agriculture, and the State Forestry Administration on Accelerating the Development of Agricultural Circular Economy.	Carrying out zero-growth action on the use of fertilizers and pesticides by 2020.

	● The Ministry of Agriculture, the NDRC, the Ministry of Science and Technology, and eight other departments jointly issued the Circular on the Program for the Construction of National Experimental Demonstration Zones for Sustainable Agricultural Development.	Accelerating the development of innovative fertilizer product technologies and increasing the use of existing enhanced efficiency fertilizers, boosting enterprises engagement in fertilizer and pesticide reduction efforts.
	● China's No.1 Central Document of 2016: Several Opinions of the CPC Central Committee and the State Council on Implementing the New Development Philosophy, Accelerating Agricultural Modernization, and Achieving the Goal of Building a Moderately Prosperous Society in All Respects.	Implementing zero-growth action on fertilizers and pesticides, stressing waste utilization, and minimizing negative impacts on the environment by demonstrating the incorporation of livestock into a crop farm.
2015	● The Ministry of Agriculture issued the Implementation Opinions on Fighting the Battle against Non-Point Source Pollution.	Lowering agrochemicals input by amount controlling and planting structure adjustment, minimizing consumption of agricultural irrigation water, and combining utilization of livestock and poultry manure, crop residues, and agricultural films.
	● Circular of the Ministry of Agriculture on Issuing the "Action Plan for Zero-Growth in Fertilizer Use by 2020" and the "Action Plan for Zero-Growth in Pesticide Use by 2020".	Setting zero-growth goal in the use of chemical fertilizers and pesticides for three major crops, such as maize, wheat, and rice, by 2020.
	● Notice of the General Office of the Ministry of Agriculture on Issuance of the Implementation Plan for Promoting Zero-Growth in Fertilizer Use by 2020.	Synergistic usage reduction and efficiency improvement of fertilizer, achieving the zero-growth goal by 2020.
	● China's No.1 Central Document of 2015: Several Opinions of the CPC Central Committee and the State Council on Stepping up Reform and Accelerating Agricultural Modernization.	Conducting in-depth soil testing and targeted fertilization, developing organic cropping systems with reduced external nutrient inputs, and transforming the agricultural sector towards a circular economy.
	● Circular of the Ministry of Agriculture, the NDRC, the Ministry of Science and Technology, and eight other ministries and commissions on issuing the National Agricultural Sustainable Development Plan (2015–2030).	Strengthening sustainable farming practices by leveraging water-saving, fertilizer-saving, pesticide-saving technologies and circular agriculture; achieving the zero-growth goal of agrochemicals use by 2020.
	● Notice of the State Council on Issuing Action Plan for Prevention and Control of Water Pollution.	Extend pilots and government subsidies for low-toxicity pesticides use with minimal residue, provide support for specialized prevention and control of pests and diseases, and deploy precision fertilization methods in response to overuse/misuse challenges.
2014	● China's No.1 Central Document of 2014: Several Opinions of the CPC Central Committee and the State Council on Comprehensively Deepening Rural Reform and Speeding up Agricultural Modernization.	To use high-efficiency fertilizers and low residue pesticides, paving the way for sustainable practices that benefit both the environment and local communities.
2012	● Notice of the State Environmental Authority, the NDRC, the Ministry of Finance, and the Ministry of Water Resources on Issuing the Water Pollution Prevention and Control Plan for Key River Basins (2011–2015).	Enacting eco-agriculture that calls for returning as much biomass to the soil as possible; supporting experiments that cater to the requirements of reducing fertilizer and pesticide use while increasing effectiveness.
	● China's No.1 Central Document of 2012: Several Opinions of the CPC Central Committee and the State Council on Accelerating the Advancement of Agricultural Scientific and Technological Innovation and Continuously Enhancing the Capacity to Secure Agricultural Product Supply.	Continuously conducting soil quality surveys and monitoring, promoting soil testing and formulated fertilization; innovating key agricultural technologies such as pest control, biodiversity conservation, and agricultural product safety.
2011	● Outline of the 12th Five-Year Plan (2011–2015) for National Economic and Social Development.	The strong focus is on controlling non-point source pollution from pesticides, fertilizers, livestock and poultry breeding in rural areas.

2007	● Notice of the General Office of the State Council Forwarding the Opinions of the State Environmental Authority on Strengthening the Work of Rural Environmental Protection.	Guide farmers to use biopesticides, or low-toxicity and low-residue pesticides, as a promising alternative to synthetic pesticides.
	● China's No.1 Central Document of 2007: Developing modern agriculture and steadily promoting the construction of a new socialist countryside.	Development of circular and eco-agriculture, reducing agricultural non-point source pollution, and giving a specific status to non-chemical and natural alternatives to conventional chemical pesticides.
2006	● Several Opinions of the CPC Central Committee and the State Council on Promoting the Construction of a New Socialist Countryside.	Raising the share of organic fertilizer application; developing conservation agriculture that focuses on minimal soil disturbance, diversifies plant species, fewer water, fertilizer, pesticides, seeds inputs.
	● Law of the People's Republic of China on Agricultural Product Quality Safety (Issued in 2006 and revised twice in 2008 and 2020).	A better use of fertilizers, pesticides, and films to prevent pollution in agricultural production areas and ensure the security of food.
	● Notice of the State Environmental Authority on Issuing the National Rural Well off Environmental Protection Action Plan.	Toward a more rational use of fertilizers, pesticides, agricultural films, and other agricultural inputs, driving the transition to ecological agriculture.
2005	● Food Safety Law of the People' Republic of China (Issued in 2005 and revised in 2015).	To upgrade best practices that minimize risks and maximize effectiveness, and conduct risk assessment of pesticide and fertilizer use.
2002	● Administrative Measures for Pollution-free Agricultural Products	Safeguarding consumer rights while ensuring the security of agricultural products and the environment through sustainable agriculture.
2001	● Regulation on Pesticide Administration (issued in 1997, revised two times in 2001, 2017)	Lowering the risks and adverse effects of pesticides on human health and the environment of agricultural production areas.
2000	● Administrative Measures for the Registration of Fertilizers (issued in 2000, revised three times in 2004, 2017, and 2022)	Forming a basic fertilizer regulatory system of product specification, labeling, safety, and efficacy evaluation; enhancing efficiency fertilizer technology and cleaner production.
1999	● Notice of the State Environmental Authority on Issuing Several Opinions on Strengthening the Work of Rural Environmental Protection.	To manage the total amount of agricultural contaminants like fertilizer and pesticide pollution by designating key control areas and targeted measures.
1993	● Agricultural Law of the People's Republic of China (issued in 1993, revised two times in 2009, 2012)	To elevate the soil fertility of farmland by stressing a better use agrochemical.

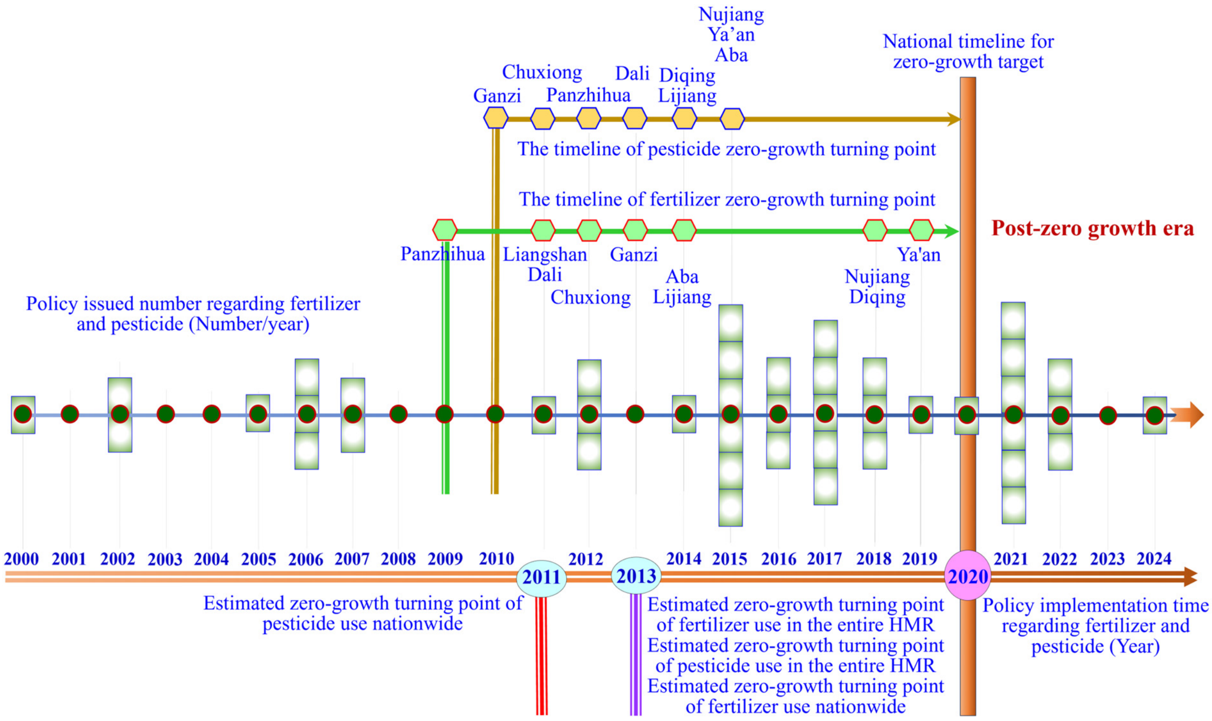


Figure 4. Timeline gaps of zero-growth inflection point at various geographical scales.

Firstly, adopting top-level design, initiating the national key R&D program for "two reductions" of fertilizers and pesticides, appears to have enhanced the technological capacity in agricultural productivity. Specifically, focusing on strategical needs of reducing fertilizer and pesticide inputs, as well as major crops like rice, cash crops, vegetables, and fruit, *etc*. Widespread technological-led initiatives announced by the Chinese government cover innovating agricultural equipment, strengthening in-depth integration of agricultural research and technological application, launching a total of 49 projects across three major fields, for example, "basic sciences, core technologies, and integrated demonstration" to boost agricultural productivity. The "two reductions" project (refer to reducing the use of chemical fertilizers and pesticides and promoting zero-growth action on chemical fertilizers and pesticides), as the largest agricultural special project during the 13th Five-Year Pan (2016–2020), involves a central government budget of CNY 2.397 billion [70]. These actions of technological innovation at different levels have resulted in a coordinated landscape and provided important drivers for reducing fertilizer and pesticide inputs.

Secondly, implementing a wider and deeper policy for improving fertilizer and pesticide application techniques, leads to a concentration of rational, precise, and scientific use capacities with respect to agricultural inputs. Similar roles may come into play with regard to implementation and enforcement of the technological path of "precision, adjustment, improvement, and replacement". Prioritizing the adoption of measures, such as deepening development of soil testing and formula fertilization; promoting integrated water and fertilizer; conducting tests for new varieties of pesticide, new formulas of pesticide, and new adjuvant technologies; exploring integrated pest management practices by the most economical means, and with the least possible hazard to people, property, and the environment around crop life cycle, may provide a robust impetus for fulfillment and enforcement of capacity in "two reductions".

Thirdly, a series of demonstration activities ranging from key regions to major crops, play a pivotal role in reducing fertilizers and pesticides use while increasing efficiency. Since 2015, by diagnosing the conditions, practices, and problems of particular groups of farmers throughout China, China's Ministry of Agriculture and Rural Affairs has conducted a broad and multifaced field pilots that encompass a wide range of experimental projects and targets, which focuses on "two reductions" in 300 counties, replaces chemical fertilizers with organic fertilizers in 233 counties, promotes green prevention and control in 600 counties, enhances healthy plants of fruits, vegetables, and tea in 150 counties, and introduces precision agriculture technologies that ensure the effective management of fertilizer and pesticide use processes [70].

Fourthly, the programs of "One Million Farmers' Training on Pesticide Use" and the 'One Hundred Experts Associated with One Hundred Counties' launched by National Agro-Tech Extension and Service Center, is accompanied by elevated safety behavior and risk cognition in farmers, and thus are closely connected with lowering pesticides consumption. Farmers, as the end-users of pesticides, must possess proper knowledge, attitude, and behaviour regarding the safe usage and storage of these compounds. This enables them to tackle complex challenges more effectively, thereby reducing environmental contamination and health problems for themselves and society. Both projects mentioned above, in terms of grain crops and major cash crops, focusing on new agricultural business entities and specialized prevention and control organizations, aim to foster more than 3 million technical backbones and farmers every year, to meet closely connecting requirements between farmers' diverse livelihood practices with the professional practices of agricultural scientists, and further drive smallholder farmers to improve use efficiency of fertilizer and pesticide along with greener production. Agricultural experts throughout the country have been organized to formulate technical programs, as a large number of promising solutions for fertilizer reduction by region and by crop, as well as providing practical guidance for farmers and new business entities to understand standard operating procedures for fertilizer reduction.

3.5. Solutions of Minimized Agrochemicals under the Post Zero-Growth Era in the HMR

Note that the list of policies related to fertilizers and pesticides in Table 3 is not intended to be a comprehensive account of how these incentives can influence agrochemicals use, but rather to provide a solid acting basis for achieving the national reducing schedule on this question. To illustrate how these actions would play out in promoting zero-growth of agrochemicals input like fertilizer and pesticide, we provide a handful of illustrative examples based on 10 administrative municipalities (autonomous prefectures) cases of the HMR. The results show that although the timelines for turning point emergence of zero-growth in fertiliser and pesticide use within the HMR were not synchronised and varied markedly, these regions have all achieved national goals ahead of 2020 deadline (see Figure 4). The timeline of the inflection point captures the core of national strategy involving fertilizer and pesticide zero-growth at both regional and national scales. These turning points have marked the transition journey towards the post zero-growth era in the HMR and the whole of China.

Not surprisingly, both intensities of fertilizer and pesticide inputs vary widely across countries and regions, however, in our comparison over 20 mountainous countries in the world, the intensities of fertilizers and pesticides use in the HMR still remain higher than most mountainous countries (see Figures 5 and 6). In particular, it is estimated that the gap of total fertilizer use per hectare of arable land, is almost 1.5–2.0-fold greater than the Alpine countries like Germany, Italy, Portugal, Greece, Romania, Austria, and Spain, *etc*., signifying there are clearly many opportunities for enhancement despite considerable achievement in reducing fertilizer and pesticide uses in the HMR. We suggest that widely shared notions of zero-growth actions could disguise or suppress other potential meanings, thereby marginalizing other policy options that could be considered more effective in the post-zero-growth era. Mountains, as a focus of the United Nations Decade on Ecosystem Restoration and the forefront of global environmental change, are fragile, vulnerable, and sensitive ecosystems where even small changes in climate or human activities can have devastating effects [71–73]. Thus, a systematic pathway aligning with major natures of the HMR is urgently needed for defending a healthier way of life, further lowering agrochemicals input in the post-zero growth era [16,24].

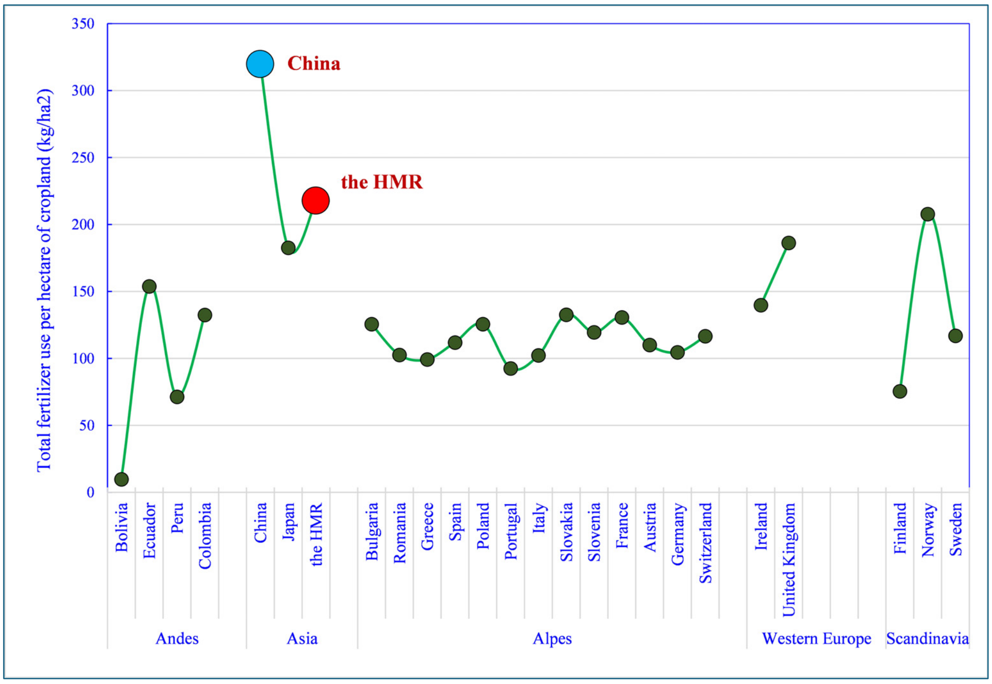


Figure 5. Comparison of HMR's fertilizer use with major mountainous countries (2021).

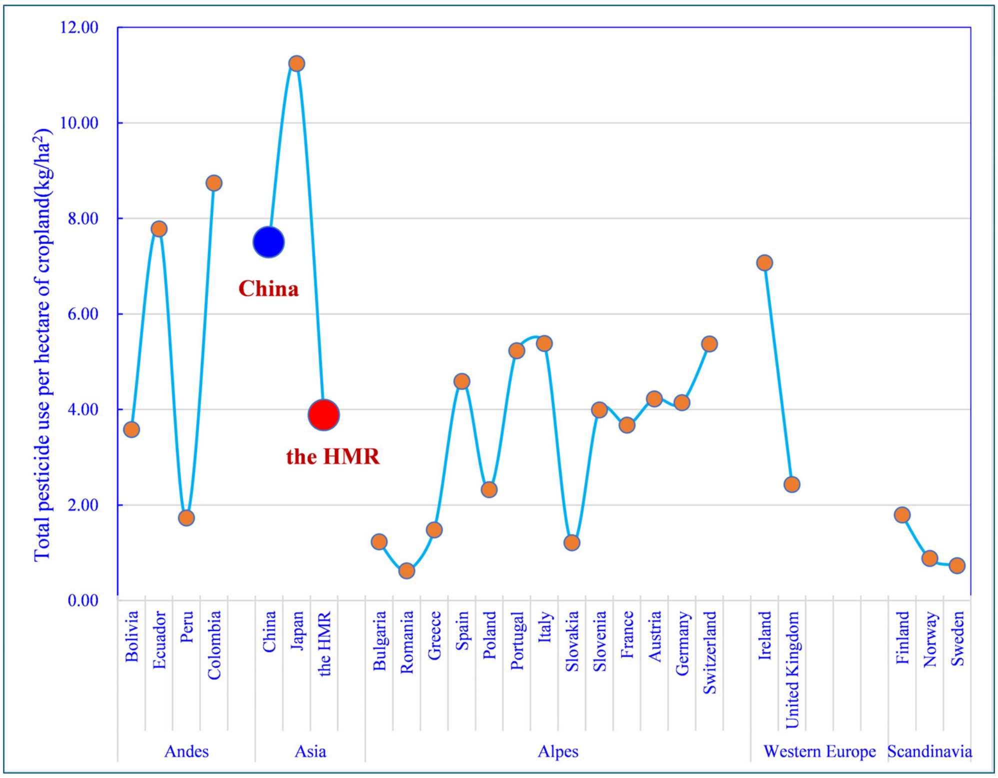


Figure 6. Comparison of HMR's pesticide use with major mountainous countries (2021).

Crop rotation-based agro-biodiversity solutions for reducing agrochemical use and environmental load. Fragmentation and terracing practice of cultivated land, as the distinguished feature of the HMR, hinder agricultural production with large-scale farming, but also provide spatial diversification of crop and non-crop habitats due to a wide range of microclimates, which support diverse ecosystems and species not found in nearby lowland areas. Adopting diverse crops and crop rotation on the same land or across different regions over successive seasons, is a potent strategy to reduce the application of agrochemicals. Specifically, according to locally adapted landraces, major strategies should include planting a variety of crops, mixed cultivation, crop rotation, intercropping, and managing habitats, aimed at developing effective conservation and enhancement of natural enemies, enhancing nutrient cycling and soil fertility, improving pest management, and boosting the resilience of agricultural structures to climate variability. For instance, most leguminous plants like beans, peas, lentils, and soybeans *etc*., contribute to soil health by fixing atmospheric nitrogen into the soil, providing essential nutrients for animals and plants, and reducing the need for synthetic nitrogen fertilizers for subsequent crops. Similarly, rotating crops, spatial diversification (different areas), and temporal diversification (seasons or interannual variability), foster a balanced ecosystem where multiple plant species disrupt pest life cycles and mitigate the risk of large-scale infestations, further reducing the incidence of pesticide resistance. These benefits of agro-biodiversity align with broader goals of reducing agro-chemicals while conserving fragile mountain ecosystems.

Organic alternative-based soil health solutions for reducing agrochemical use and environmental load. The HMR' farming systems that have evolved under varying agroclimatic conditions include diverse crop cultivation, changing lifestyles, and deconcentrated individual farmhouses and agricultural activities. These prominent features suggest that approaches to reducing agrochemicals use in mountain agriculture are varied, rich, and dynamic, with innovative and traditional farming practices. Substituting chemicals with crop straw and human-livestock-poultry manure, harnessing the potential opportunity of organic farming systems, is key to cutting disposal costs even creating new income for rural residents, and ensuring that healthy mountain ecosystems can continue to provide their essential services in the HMR. Growing practices in the HMR, like potatoes, beans, maize, buckwheat, barley, rice, fruits, and vineyards, are widespread among organic as well as inorganic farmers. In recent years, organic agriculture in this region has been officially promoted by Yunnan province and Sichuan province, respectively. For example, Yunnan' science and technology department launched a major project entitled "Research and Application of Technologies for Plateau Organic Agriculture in Yunnan". Xichong, as the capital of Liangshang Prefecture, in Sichuan province, is known for its early efforts in promoting organic agriculture at the county level. Organic agriculture in the HMR should be emphasized by several core approaches that underscore its role in promoting organic mountain farming systems. Owing to the terraced system on a steep slope, it is very susceptible to hydrogeological instability [74]. One fundamental approach is to support investment in infrastructure such as natural pest traps and irrigation systems, which emphasizes the importance of funding in maintaining stable and sustainable services. Subsidies for organic input provide financial assistance to producers (rural enterprises, villages collective organizations, and smallholder farmers) who are certified organic or transitioning to certified organic agriculture by distributing free seeds, encouraging farmers to plant cover crops that can be used as "green manure" and improve soil organic matter. Another crucial solution is organic branding and positioning strategy. Because a smooth supply chain and targeted market measures are especially relevant for scaling up the adoption of organic agriculture by most of farmers in remote areas. Emphasis should be placed on building a direct connection from farm to table to maximize farmers' chances of success. Smart mixes of context-specific policies involving organic practices are another central strategy for more contextualized policymaking. This approach to problem-solving focuses on the differentiation and suitability of an organic action plan in diverse regions.

Professionalization-based precision farming solutions for reducing agrochemical use and environmental load. Because of topographical constraints, the HMR are typically characterized by limited flat ground, limited arable land, and marginalization, creating natural barriers that affect specialized agricultural practices. However, major crop-producing areas with favorable geo-climatic conditions like Anning River plain, Chuxiong, Dali, and Panzhihua *etc*., has undergone a shift from labor-intensive to capital-intensive farming in agricultural specialization [75,76]. At the same time, urbanization and globalization have fueled the emergence of precise farming, specialized, high-yielding, and eco-friendly agricultural systems. A vast literature also studies the relationships between agricultural specialization, intensification, and chemicals reduction. They suggest that agricultural specialization reduced the usage of fertilizers and pesticides through balanced fertilization treatment, unified defense rule and pilot projects [20,25,77]. This highlights the importance of considering concentrated agricultural bases or agro-industrial parks, such as vegetables, fruits, horticulture, and grain crops commodity areas as a priority target for reducing chemical fertilizers and pesticides. Particular attention, in the process of large-scale agricultural production and high-standard farmland construction, should be paid to curbing the susceptibility to soil erosion accompanying introduction of heavy or non-optimal mechanization. Farmland transfer and agricultural cooperatives are responsible for most chemicals-related issues. The intensive use, precision formulas of chemical fertilizers and pesticides in agriculture contributes significantly to decreasing chemicals input. Transforming from a single farmer to an agricultural enterprise that encompasses the distribution of technology through extension services, the sharing of information, and the adoption of agricultural technology can play a pivotal role in controlling the intensity of agrochemicals application. In fact, moderate-scale agriculture changes the ways of seeding, planting, producing, and marketing full linkages. Apparently, a muti-facet specialized approach which considers unified defense and control, adopting soil-fertilization management techniques, using conservation drainage practices, establishing strict quality standards for agricultural products, increasing investment in agricultural mechanization, balancing agricultural production benefits, ensuring year-round ground cover, *etc*., is necessary and possible to reduce reliance on chemicals in mountainous agriculture.

Smallholder farmers' awareness-based behavior intervention solutions for reducing agrochemical use and biologicals as safer alternatives. Smallholder farming, a major source of livelihood for 9.7 million rural people, is the main body of agricultural activities in the HMR. A recent survey found that farm size is a strong factor that affects the use intensity of agrochemicals across farms in China [78]. There is a substantial literature showing that smallholder family can indeed increase the intensities of fertilizer and pesticide inputs [20,25,26,78,79]. This demonstrates that efforts to remove existing barriers to small farmers' awareness of the risks to human health and the environment can help complement other remedies to the overuse problem in the HMR. It is imperative that small farmers and communities, especially those in rural and agricultural areas, are educated and made aware of safe practices in handling and applying agrochemicals. To effectively raise awareness and educate rural communities about agrochemical reduction and safety, a condition-specific care should be emphasized: organizing workshops and training sessions in local communities to strengthen knowledge regarding biologicals as a safer alternative; integrating agrochemical safety education into the curriculum of local schools; leveraging various media platforms like WeChat, radio and brochure disseminating information widely and quickly; involving community members in research on agrochemical use and its impacts associating increasing income; setting behavior-based safety rewards for local farmers. In summary, partnering with farmers and facilitating information exchange to mitigate the disadvantages of isolation, accessibility, harsh climate, threatened ecosystems, erosion, soil degradation, and the frequency of natural hazards in the HMR, plays a tremendous role in separate small farmers' willingness and behaviors to change.

Conservation reserve-based zoning solutions aim to reduce agrochemical use and environmental effects. Apart from a large number of national, provincial, and municipal nature reserves, the HMR, as the most biologically diverse temperate region on Earth, is home to four UNESCO World Heritage sites including Old Town of Lijiang, Three Parallel Rivers of Yunnan Protected Areas, South China Karst, Sichuan Giant Panda Sanctuaries, showcasing its natural beauty, cultural heritage, and biodiversity. Buffer zones with multiple types and wide areas, may foster better soil quality on agricultural land, as well as sustainability of natural reserves and rural livelihood by optimalization structure of agricultural chemicals use and reducing their input intensity. Therefore, the strengthening of management targeting agrochemicals use in the HMR is urgent and potential for sustainable development of both local farmers' livelihood and heritage sites. Different buffer zones or the same buffer strip width with different vegetation cover varies effects of agrochemicals load [2,80]. Thus, zoning strategy can minimize issues related chemical fertilizers and pesticides use by delineating areas for prohibiting substances applied to adjacent farming zones. Local governments in collaboration with scientists in multidisciplinary fields should delve into the specifics of chemicals use zoning, what it allows, and its broader implications. Attention will be drawn to the spectrum of policies aimed at nurturing and empowering local farmers, achieving harmony between communities and nature reserves. With buffer and experimental zones as the basis, government initiatives, such as value-added producer grants and conservation stewardship program, support local agricultural companies and farmers looking to transition to or expand their high value-added goods practices for fostering biodiversity, increasing income, boosting economic growth, creation of wealth at the local farmers' level, and promoting the health of the land in the long term. It is extremely important to prevent drift or runoff of chemical fertilizers and pesticides onto organic fields or core zones of natural reserves. Furthermore, more attention is paid to reducing chemical fertilizer and pesticide risks by using nature-based solutions such as biological control, the use of natural biopesticides, reintegrating straw into fields, restructuring and managing farm systems by immune and metabolic functions, balancing between plant diversity and soil microbial ecology, integrated crop and pest management, *etc*.[16,18,81]. This preventative strategy mainly relies on key practices in the design of pest resilient, soil fertilization maintenance, and healthy agroecosystems.

4. Concluding Remarks

The time span (in years) of fertilizer zero-growth in 10 municipalities (prefectures) in the HMR is relatively wide, with a distribution from 2009 to 2019. On the contrary, the occurred turning point of zero-growth in pesticide was concentrated between 2010 and 2015. Although the HMR lags behind the national average overall, all municipalities (prefectures) have been achieved national goals ahead of 2020 deadline.

The incentives of a series of national-level policies focusing on chemical fertilizers and pesticides, have proven effective in achieving zero-growth target of agrochemicals input in the HMR. Especially since 2015, a wide range of policies have been adopted at the state level to accelerate lowering agrochemicals and environmental load, creating a powerful driving force for ensuring food production, preserving the environment, and responsibly managing natural resources. The MHR, relying on mountainous conditions, have continued to implement natural way of farming such as developing eco-friendly agricultural products by emphasizing ecological relationships, reducing chemical inputs, restoring soil fertility, and expanding profit horizons by special agricultural products such as tea, flowers, buckwheat, fruits, vegetables and Chinese herbs, which has laied a solid foundation for reducing chemical fertilizers and pesticides use.

Due to complex reasons such as a corrugated landscape of deep river gorges and tall dividing ranges, climatic variability, fragmented land, and ethnic concentration, *etc*., the intensity of fertilizers and pesticides use in the HMR, despite declining markedly and achieving zero-growth target, still remains high when compared to major mountainous countries. It has been demonstrated that there is still a lot of space and opportunity for reducing agrochemicals use in the post-zero growth era in the HMR. As existing research states, there is no one-size-fits-all solution to mitigating the environmental effects of agrochemicals input in mountainous areas. In short, we need a solution fitted the HMR for minimizing reliance on external inputs. A lot of time is spent on allowing or minimally reducing the allowable quantities rather than fostering a future where chemical intervention is minimized. This is particularly important in exceptionally fragile and highly sensitive mountain areas. Our proposed strategies, which include crop rotation-based agro-biodiversity solutions, organic alternative-based soil health solutions, professionalization-based precision farming solutions, smallholder farmers' awareness-based behavior intervention solutions, and conservation reserve-based zoning solutions, not only advocate lowering chemical practices but also present a practical route to balancing humans and the environment in the HMR.

Author Contributions

Conceptualization, Y.F.; Methodology, Y.F.; Formal Analysis, Y.F.; Data Curation, Y.F.; Writing—Original Draft Preparation, Y.F.; Writing—Review & Editing, Y.F. and X.H.; Visualization, Y.F.; Supervision, Y.F.; Funding Acquisition, Y.F.

Ethics Statement

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Informed Consent Statement

Not applicable.

Data Availability Statement

Data available on request/reasonable request.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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