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Fallow priority areas for spatial trade-offs between cost and efficiency in China

Siyan Zeng[1,2,3], Fu Chen[4]✉, Gang-Jun Liu[5], Estelle Raveloaritiana[2,3] & Thomas Cherico Wanger[2,3,6,7]✉

Fallow pilot policies exist in China but fallow priority areas have yet to be identified based on eco-environmental stressors and spatial cost-benefit analyses. Here we use a multi-criteria optimization algorithm to determine fallow priority areas based on soil pollution, groundwater overexploitation, land quality, and ecological protection redlines delineation data and with high-cost effectiveness. By considering five spatial scenarios on three objective functions, we find most notably that fallowing the top 20% of priority areas, the benefit of pollution control and environmental protection can be achieved by up to 98.7% and 64.7%, respectively. Our results show that effective fallow prioritization on cultivated land may reduce implementation costs by up to 509.3 billion USD, corresponding to 13.6% of China's budget in 2021. Thus, effective fallow prioritization will promote sustainable land use by pursuing goals between benefits and cost synergistically and allow budget allocation to other sustainable agricultural targets based on agricultural diversification.

[1] College of Environmental and Resource Sciences, Zhejiang University, Hangzhou, China. [2] Key Laboratory of Coastal Environment and Resources of Zhejiang Province, School of Engineering, Westlake University, Hangzhou, China. [3] Sustainable Agricultural Systems & Engineering Lab, School of Engineering, Westlake University, 18 Shilongshan Road, Hangzhou, China. [4] School of Public Administration, Hohai University, Nanjing, China. [5] Geospatial Science, School of Science, STEM College, RMIT University, Melbourne, VIC 3000, Australia. [6] GlobalAgroforestryNetwork.org, Hangzhou, China. [7] ChinaRiceNetwork.org, Hangzhou, China. ✉email: chenfu@cumt.edu.cn; tomcwanger@gmail.com

The global agricultural system needs to guarantee sufficient and sustainable food production for a growing population while curbing the environmental deterioration of cultivated land caused by industrial agricultural practices[1]. In addition, food safety is essential to human health[2], while over five million soil sites worldwide are contaminated with toxic elements[3]. Different strategies have been suggested for major policy initiatives to mitigate soil erosion, severe groundwater overdraft, soil degradation, and reducing soil pollution for instance through agricultural diversification, phytoremediation, and fallow[4–6]. Fallow cultivated land is an agricultural technique involving the ecological process whereby farmers stop farming for a period and it is practiced globally[7].

Fallow systems have long been used to reduce negative externalities such as excessive water use during production, and to increase yields by recovering soil nutrients[8–10]. In China, fallow cultivated land encompasses multiple series of measures such as engineering treatment, phytoremediation, or soil restoration to enhance soil fertility, remediate pollution, and improve cultivated land environments (MARA of China, 2019). And recently, the Chinese government advocates the use of fallow as an effective strategy to solve ecological degradation in cultivated land[11], and to promote sustainable agricultural development. Indeed, within Chinese agricultural policy, fallow has been identified as a key measure for a cost-effective strategy to protect cultivated land[12] and to reduce soil pollution for ensuring food safety[13,14], while at the same time aiming to increase grain production and ensuring national food security[15]. However, the Chinese policy does not yet include any guidance to implement fallow with win-win scenarios between ecological and economic leverage points[16]. More specifically, it is not yet known where fallow implementation in food production or ecological benefits may be achieved with the least cost.

Spatial trade-offs are recognized globally as an effective approach in spatial decision-making of land use[17]. Currently, most published studies focused on either statistical analysis of trade-off relationships or optimized representative trade-offs related to ecosystem services, biodiversity conservation, restoration priorities, and protected zones[18–20]. However, no research shows the benefits of prioritizing fallow zones at the national scale and evaluating the spatial cost-benefit trade-offs. Previous studies of the fallow implementation scale in China mainly focused on predicting the recommended fallow ratio based on food demand considerations[21–24] or quantifying fallow at the regional scale based on a single aspect of cultivated land due to the data limitation at the national scale[7]. For example, from the perspective of land use change from 1990 to 2017, Lu et al.[21] estimated the grain production potential of existing and unexcavated cultivated land to get the theoretical fallow scale under the regionally differentiated per capita grain consumption levels in China. Liang et al.[23] considered arable land holdings volume and the minimum food security bottom line constraints of China in 2035, 2050, and 2100 to set fallow thresholds, with an annual fallow ratio up to 13.57%, 10.65%, and 31.51%, respectively. However, these preceding studies had limitations as they only determined the fallow scale but without spatial analysis[7,25,26]. Furthermore, the Chinese government has adopted the voluntary declaration and total scale control approach to implementing fallow from the bottom up[15]. The fallow programs piloted so far have clarified neither the fallow urgency of eco-environmental stressors nor the spatial trade-off analyses between environmental and economic costs and benefits.

Here, we applied a multi-criteria optimization algorithm and combined multisource data to fill these gaps by evaluating the trade-offs between environmental and economic costs and benefits of the fallow system in China. Based on this approach, we answered where to fallow could lead to the most cost-efficient management decisions. Based on the four main eco-environmental stressors of fallow cultivated land (1) soil pollution[6,27,28], (2) groundwater overexploitation[7], (3) quality of cultivated land[6,7], and (4) ecological protection redlines (EPR) areas[29], we optimized the spatial trade-offs of fallow across five scenarios, focusing on three objective functions on environmental and economic costs and benefits. To give realistic fallow recommendations, we determined a 20% upper limit of fallowing the total cultivated area (see the section "(2) Fallow scale constraints" below). Our study shows that multi-objective decision-making methods are advisable if trade-offs between benefits and costs of fallow implementation are to be enhanced. We call for further fallow programs in China to be oriented towards overarching cost-benefit efficiency to guide cultivated land degeneration prevention programs and promote sustainable cultivated land use.

Results

Spatial distribution of eco-environmental stressors on cultivated land. Across China, 77.9% of cultivated land is unpolluted, 18.6% is slightly polluted, and 3.5% suffers moderate to severe soil pollution (Fig. 1a). Soil pollution in southern China is serious, displaying a large dispersed distribution pattern, unlike the point distribution in the north. Almost all the moderate and severe polluted areas are distributed to the east of the "Hu Huanyong line", such as cultivated land located in Jiangsu, Hunan, and Jiangxi provinces (names and locations of the provinces are shown in Supplementary Fig. 2).

Only 29.5% of arable land is rated good or excellent based on the quality grading of cultivated land. The good or excellent arable land is located mainly in the eastern region with relatively flat terrain, high-quality water for irrigation, and adequate rainfall (Fig. 1b). By contrast, about 17.7% of arable land is rated poor or inferior and is distributed mainly in the northwest region characterized by poor quality irrigation water, inadequate rainfall, and hilly topography.

In 91.8% of all cultivated land, groundwater use is balanced (Fig. 1c). Only 4.5% of cultivated land suffers moderate to severe groundwater exploitation, scattered across the arid regions of Xinjiang, Gansu, Shaanxi, and Hebei. The biggest area of overexploited groundwater was found in Hebei and Henan, covering ~4670 km^2, and 3950 km^2, respectively.

Two classes of EPR were distinguished based on the *Guidelines for the Delineation of Ecological Protection Redlines*[30]. Across China, 85.5% of cultivated land was located outside of the delineation of EPR, and 14.5% was located within the first- or second-class EPR, respectively (Fig. 1d). The cultivated land found within the first-class EPR, where the ecosystem services are extremely important, and the environmental sensitivity is extremely sensitive, was largely clustered in the hilly and gully areas near the Loess Plateau. The cultivated land in the second-class EPR was mainly clustered in the Changbai Mountain Ecological Function Reserve at the border of Heilongjiang and Jilin.

Priority areas for fallow. We found differences in spatial distributions of priority fallow areas especially in scenarios, where the focus was solely on achieving pollution control benefit (Fig. 2a), or environmental protection benefit (Fig. 2b), or reducing the cost associated with implementing fallow (Fig. 2c). The differences highlight the importance of both comprehensive trade-off analyses and multi-objective optimization, with rationally selected priority fallow areas and different objective strategies (Fig. 2d, e).

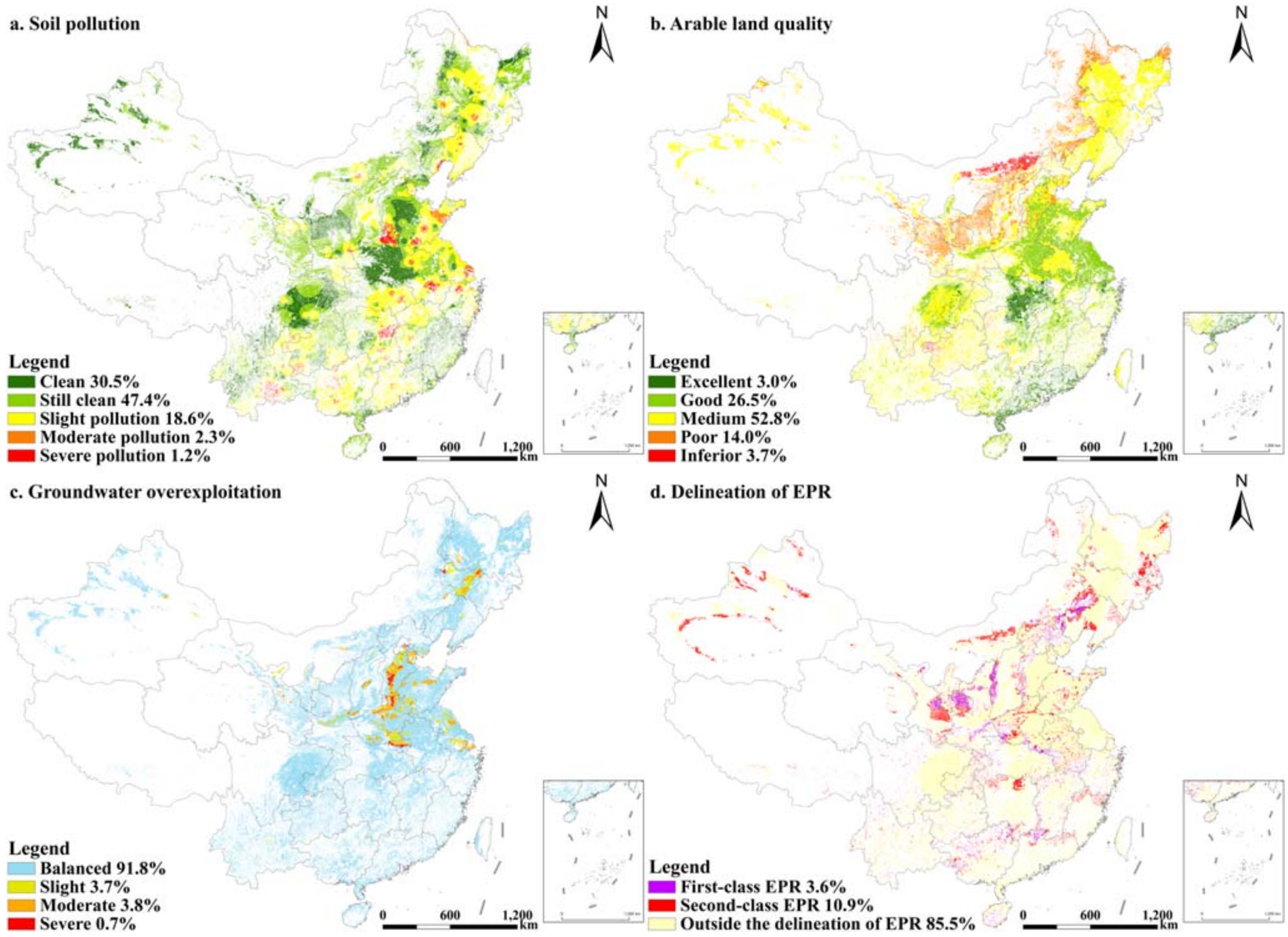

Fig. 1 Spatial distribution of eco-environmental stressors on cultivated land in China (note: EPR represents the ecological protection redlines). a Soil pollution. **b** Arable land quality. **c** Groundwater overexploitation. **d** Delineation of EPR.

When focused on maximizing the percentage of the pollution control benefit in the priority to risk mitigation scenario (PMS), fallow priority areas were mainly concentrated in the south-eastern part of China (Fig. 2a). The distribution of the top 3.4% fallow priority areas in PMS was homologous to the spatial pattern of cultivated land's moderate and severe pollution degree, as these areas corresponding to the high concentration for carcinogenic heavy metals, including Cr, Cd, and Pb (Supplementary Fig. 9). When focused on maximizing the percentage of environmental protection benefit in the priority to ecological civilization scenario (PES), the top 4.3% fallow priority areas were mostly concentrated in the northern and central regions of China (Fig. 2b). When focused on minimizing the cost associated with implementing fallow in the cost reduction scenario (CRS), large-scale fallow priority areas were concentrated in the northern and western area of China (Fig. 2c).

When we considered the combination of the pollution control and environmental protection benefit in the multiple benefits scenario (MBS), the spatial distribution of the top 4.2% fallow priority areas was mainly concentrated in the hilly and gully areas close to the Loess Plateau in Gansu, the junction of Henan and Hebei, southeastern Inner Mongolia, and southern Anhui (Fig. 2d). When all three criteria (including maximizing pollution control benefit (RI_i), maximizing environmental protection benefit (EP_i), and minimizing fallow implementation cost (CT_i)) were simultaneously considered in the comprehensive fallow scenario (CFS, Fig. 2e), the top 8% fallow priority areas had a similar spatial distribution to that shown in the cost reduction scenario (CRS, Fig. 2c). The priority fallow areas in these two scenarios (Fig. 2c, e) are more scattered than the other three scenarios (Fig. 2a, b, d), while the top 20% fallow priority areas in the northeast area of the comprehensive fallow scenario (CFS) is much higher than the cost reduction scenario (CRS).

Outcome evaluation. Cost-benefit differences exist between the five spatial scenarios of priority fallow areas (Fig. 3). When the top 2.1% of fallow areas are considered, benefits for the maximized percentage of pollution control, vary 95.0 times for the same fallow percentage ($\alpha = 23.5\%$, ranging between 0.3% in the cost reduction scenario (CRS) and 23.8% in the priority to risk mitigation scenario (PMS)) (Fig. 3a). Benefits for the maximum percentage of realized environmental protection vary over eightfold and β=9.9%, vary from 1.3% in the cost reduction scenario (CRS) to 11.2% in the priority to ecological civilization scenario (PES)) (Fig. 3b). The minimum total cost of fallow implementation of 2.1% area differed by 192.8 billion USD on average, and the corresponding costs range of scenarios 1–5 is 152.2–242.7 billion USD, 29.4–41.3 billion USD, 3.9–8.7 billion USD, 138.2–256.9 billion USD, and 8.5–20.7 billion USD, respectively (Fig. 3c).

When 20% of priority fallow areas are considered, the maximum percentage of the pollution control differed by 85.9%, ranging between 12.8% in the cost reduction scenario (CRS) and 98.7% in the priority to risk mitigation scenario (PMS) (Fig. 3a). However, the maximum percentage of realized environmental protection benefit is 64.7% in the priority to ecological civilization scenario

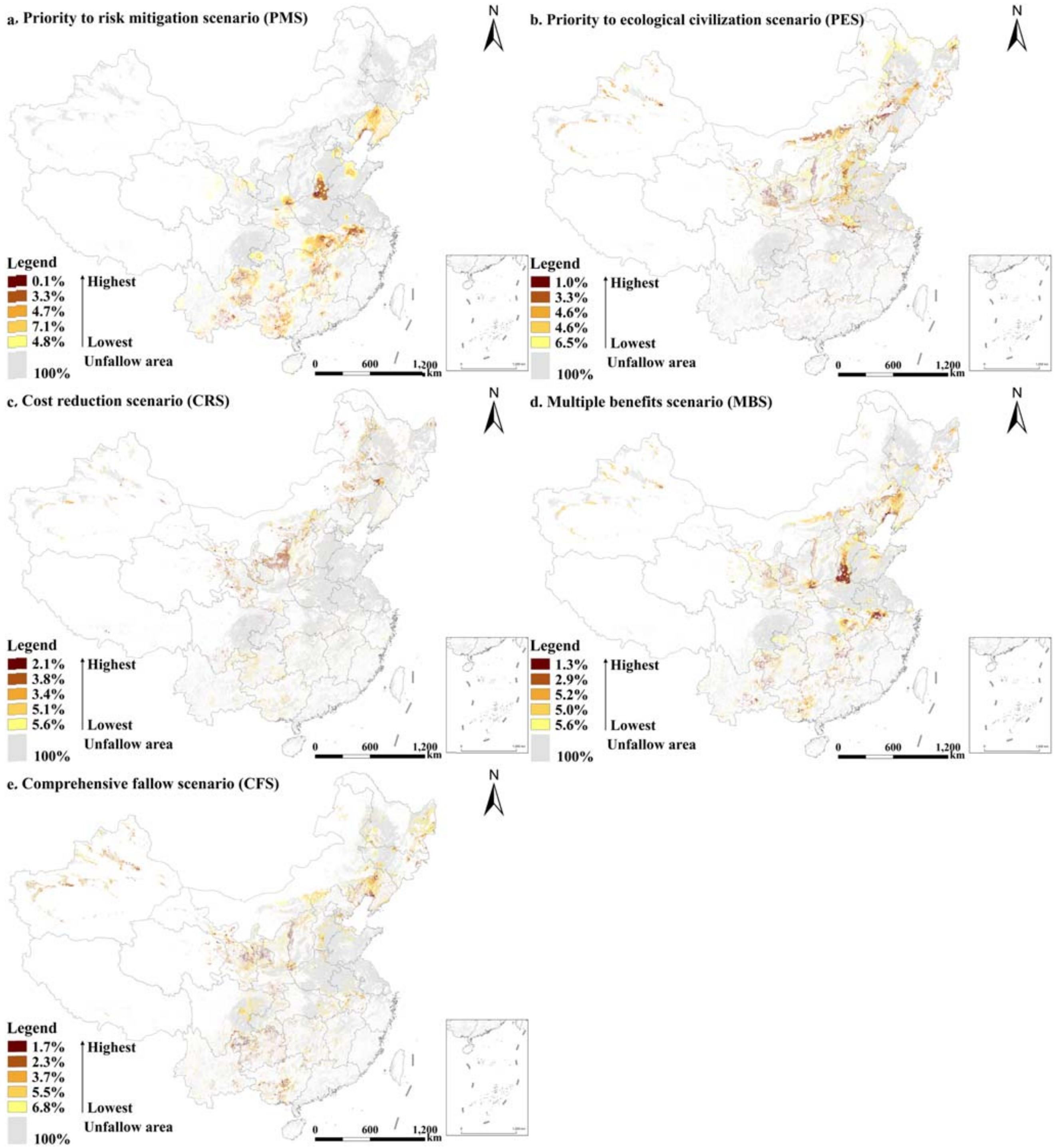

Fig. 2 Spatial trade-off analysis to identify priority fallow cultivated land areas in China. **a** Priority to risk mitigation scenario (PMS). **b** Priority to ecological civilization scenario (PES). **c** Cost reduction scenario (CRS). **d** Multiple benefits scenario (MBS). **e** Comprehensive fallow scenario (CFS).

(PES), showing 42.4%, 48.1%, 32.5%, and 38.11% higher than in the PMS, CRS, MBS, and CFS, respectively (Fig. 3b). The total cost of fallow implementation differed by 6.7 times at the minimum cost, while differed by 7.4 times at the maximum cost, ranging 56.6–79.4 billion USD in the CRS and 380.4 –588.7 billion USD in the PMS (Fig. 3c). Overall, priority fallow of 20% of the cultivated land in the comprehensive fallow scenario (CFS) could achieve up to 28.8% of pollution control benefit (Fig. 3a) and realize at most 26.6 % of environmental protection benefit (Fig. 3b), with only cost 65.5–95.6 billion USD (Fig. 3c). When compared with the cost reduction scenario (CRS), priority fallow of 20% of the cultivated land in China can minimum reduce 323.8 billion USD, or maximum reduce 509.3 billion USD (Fig. 3c).

Discussion

We quantify the benefits for, and costs of, multiple targets to use fallow for pollution control on human health risk mitigation and environmental protection such as by cleaning up severely polluted, poor or inferior quality, and severe groundwater

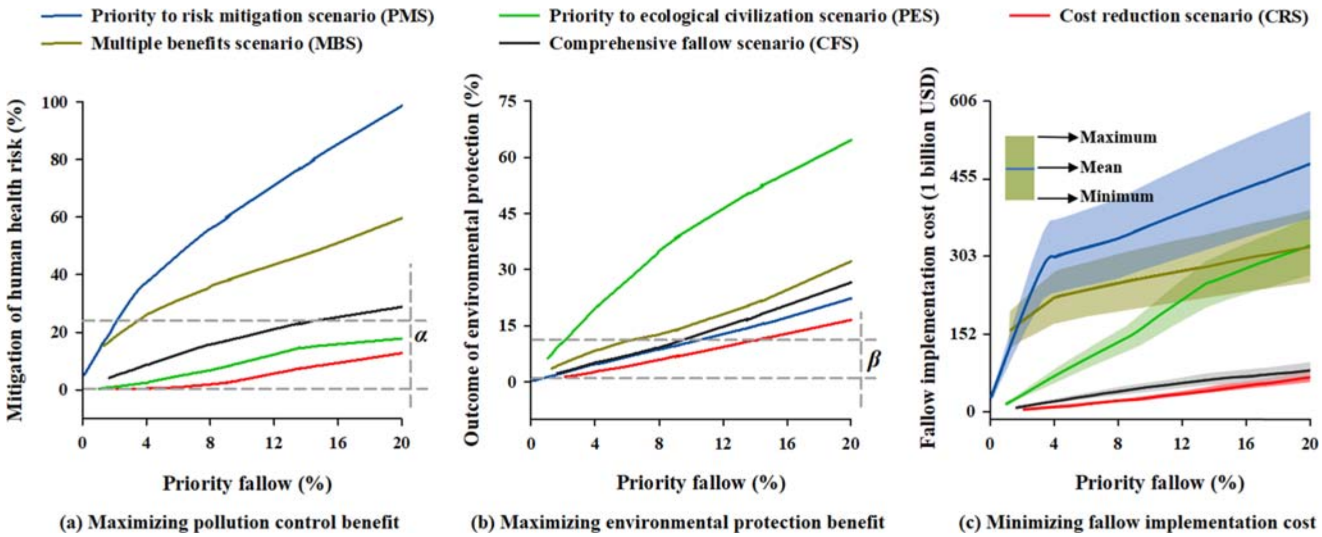

Fig. 3 Different outcomes of the five spatial scenarios of priority fallow areas (note: 100 USD = 660 CNY). **a** Maximizing pollution control benefit. **b** Maximizing environmental protection benefit. **c** Minimizing fallow implementation cost.

exploitation cultivated land. We find that by implementing a 20% priority fallow strategy on the total cultivated land, 98.7% of pollution control benefit can be achieved under the priority to risk mitigation scenario (PMS). When compared to the priority to risk mitigation scenario (PMS), fallow implementation costs can be reduced by up to 509.3 billion USD under the cost reduction scenario (CRS), which is accounting for 13.6% of China's public budget expenditure in 2021. It means that effective fallow prioritization will allow national budget allocation to other sustainable agricultural targets based on agricultural diversification[4]. Our scenario-based analysis suggests that fallow implementation requires a spatial differentiation pattern with a multi-objective decision-making method. The spatial differentiation pattern highlights that area alone is an ineffective metric for balancing the benefits and costs of fallow implementation at a national scale, with up to 95.0 times and over eightfold variation in outcomes for the same fallow percentage of the pollution control benefit and environmental protection benefit, respectively. These results show that location-specific fallow implementation should instead be oriented towards overarching cost-benefit efficiency to guide soil pollution and cultivated land degeneration prevention programs in China.

The large population and limited cultivated land resources in China makes identifying an appropriate fallow scale a critical issue without affecting national food security and in parallel leading to the most cost-efficient management decisions under resources and environmental constraints. To address this urgent issue, the majority of current studies only focused on theoretical analyses to explore the implementation framework but lack precise data for systematic computations[15,31]. Some studies focus on the fallow scale at the national level and provide the appropriate fallow scale in relation to the population carrying capacity of land[32], national food security[22–24], or land use change[21]. Location-specific information is critical because it can help to avoid the mismatch between voluntary fallow land declaration by farmers and the areas that require fallow implementation. Our study provides specific answers of where to fallow but followed the recommended upper scale limit of 20%[33,34]; in contrast the existing literature only gives fallow ratios[35,36]. In addition, the selection of four co-environmental stressors is consistent with previous studies and the specific requirements of fallow policy in China, which enhanced the reliability of our research findings on fallow priority areas. Our priority fallow areas are consistent with the current fallow pilots' location[3,7,27,37,38], such as heavy metal contaminated zones of Hunan province in our priority to risk mitigation scenario (PMS) and the groundwater overdraft zone of Henan province in our priority to ecological civilization scenario (PES).

We acknowledge two caveats with our study related to the soil pollution data sources and the social implications. The used soil pollution data is necessarily suffering from carry-over effects of limited resolution and outliers of the sample distribution in the sourcing studies, which may affect our pollution control benefit evaluation and the restoration priority areas for fallow. We accounted for this caveat by using the [x/4, 4x] method to verify that outliers do not affect the actual fallow priority results (sensu[39,40]; for more details see Supplementary Note 6). Furthermore, the mapping resolution of 1 km^2 in our study meets the requirement of the Chinese national fallow policy, which is much smaller than the most basic administrative statistical unit of a village in China, while the fallow pilot program is implemented with the smallest unit generally no smaller than a village[6]. Moreover, social factors such as the willingness of farmers to fallow will affect the practical implementation of our results. While this is an important issue, to our knowledge the relevant data with appropriate resolution was not available at the time of writing and we considered this aspect to be beyond the scope of this study.

Current fallow pilot programs in China can be divided into two types: crop rotation and full fallow, consisting of different measures on soil restoration[6], which means that the definition of fallow is not limited to land "rest" (MARA of China, 2019). For instance, the "managed fallow mode" focuses on improving soil physicochemical properties and decreasing pollutants content by combining long-term remediation measures[27]. The "fertilizer enrichment mode" includes tillage and sunning, growing winter green manure crops, intercropping with bean crops, and focuses on removing continuous cropping obstacles in low arable land quality areas[20]. However, the voluntary declaration and total scale control approach make the spatial characteristics of cultivated land resources among different pilot areas insufficiently considered, but these characteristics determine broad-scale fallow implementation priorities. Besides this, as the Chinese policy definition of fallow is admittingly far-reaching and broad[20,21,27], we discuss the question of where to fallow in China without specifying how to fallow (e.g fallow mode, time allocation, etc.).

Thus, our study considers the spatial distribution of the four most urgent eco-environmental stressors and costs influencing fallow programs implementation on cultivated land in China. The fallow targets should be oriented towards multiple outcomes, including pollution control, environmental protection, and cost reduction, which can enhance the fallow implementation efficiency and maximize benefits at minimum cost.

Previous studies on the national level of fallowing focused on the fallow scale calculation from the food demand perspective but without spatial analysis. We fill this research gap by identifying the trade-offs among maximizing the pollution control and environmental protection benefits while minimizing fallow implementation cost, and then identifying priority fallow areas under different scenarios. Our study is different from previous work when comparing the consideration of indicators in our multi-objective function. Besides considering four eco-environmental stressors of fallow cultivated land, we calculate fallow implementation cost comprehensively for the first time at the national scale. The trade-off decision-making tools can be applied to support fallow planning practices and optimize the spatial-temporal allocation of fallow areas at the national, regional, and local levels. Such a trade-off assessment could be done by investigating cost-benefit efficiency to decrease unsustainable land use, similar to ecosystem restoration or consolidation of agricultural land studies[16,41]. Spatial distribution of eco-environmental stressors on cultivated land provides the basis for identifying the fallow priority areas, and then for tracking fallow implementation towards soil pollution control and environmental protection, as well as applying cultivated land condition monitoring to support decision-making. By mapping the priority fallow areas of different scenarios and quantifying the efficiency on benefits and cost, our findings underscore that - if well-planned, fallow prioritization can make substantial headway on enhancing implementation efficiency towards addressing the most urgent issues under limited funds. This study provides a comprehensive overview of fallow priority areas and offers specific data to decision-makers to achieve the goal of eco-environment protection in China and the global food systems transformation through enhanced soil conservation efforts.

Methods

Data collection and processing. Soil pollution data were obtained from our previous research results[40] and are based on 553 peer-reviewed articles that report soil pollution data for 1781 soil sample locations, including 5597 samples with average concentrations of eight pollutants (see Supplementary Note 2). Data on the quality grades of cultivated land were derived from China's cultivated land quality grade evaluation released by the MLR in 2015[42]. The data on groundwater overexploitation was extracted from the 1979 and 2011 *Shallow Groundwater Level Contours and Burial Depth Atlas* published by the hydrogeological Survey Center of China Geological Survey (CGS)[43]. The groundwater overexploitation data was derived according to the *Guidelines for the Assessment of Groundwater Overexploitation Zones* (GBT34968-2017)[44] and modified with *the Distribution of China's Major Groundwater Overexploitation Areas* (2004)[45] and *the Atlas of Groundwater Resources and Environment in China* (2006)[46] released by the Department of Water Resources of the Ministry of Water Resources and the Nanjing Hydraulic Research Institute. The delineation of ecological protection redlines (EPR) was delineated according to *the Guidelines for the Delineation of Ecological Protection Redlines* issued by the Ministry of Environmental Protection (MEP) and the National Development and Reform Commission (NDRC) of China. The importance of ecosystem service and the environmental sensitivity were evaluated (see Supplementary Note 3) to generate a spatial distribution map of the EPR in China by complementing with datasets from various sources, as listed in Supplementary Table 2. The delineated EPR was then also compared with the released EPR of 20 Chinese provinces[47] to make the correction of the spatial distribution map of the EPR by using the overlay analysis on ArcGIS 10.6 (ESRI, Sacramento, CA, USA).

Analysis of eco-environmental stressors for cultivated land. We identified the four main eco-environmental stressors of fallow cultivated land (1) soil pollution[27], (2) groundwater overexploitation, (3) quality of cultivated land, and (4) ecological protection redlines (EPR) areas. We chose the former two, because they are prioritized in the national fallow policy[6,28]. The latter two, are used in previous studies to select barren land[7] and to alleviate the conflict between arable land use and environmental protection[29], respectively. For more details on eco-environmental stressors selection, see Supplementary Note 1.

Assessment of soil pollution. Soil pollution is mostly composite pollution and single-element pollution rarely occurs[39]. Therefore, the single factor index and the Nemerow integrated pollution index were used in this study to analyze the degree of soil pollution (Supplementary Note 4). Due to the various types of pollutants in Chinese cultivated land, those collected eight pollutants for the soil pollution assessment, including heavy metals (Cr, Cu, Cd, Pb, and Zn), organic pollutants (HCHs, DDTs), and PAHs, which are the most important soil contamination in China and the main pollutants required to be monitored by the Chinese soil environmental quality standards, *Soil environmental quality risk control standard for soil contamination of agricultural land* (GB15618-2018)[48]. The assessment standard value S_j of pollutant j was obtained from the *Soil environmental quality risk control standard for soil contamination of agricultural land* (GB15618-2018)[48]. The pollution standard of total PAHs content is the categorized standard threshold value (<200 $\mu g\ kg^{-1}$)[49] (Supplementary Table 4). The soil quality standards listed in the *technical requirements for regional ecosystem geochemistry assessment* (DD2005-02)[50] were used to classify the soil composite pollution index PI of cultivated land, which was classified into five categories (Supplementary Table 5).

Quality grading of cultivated land. Arable land quality in China is rapidly declining due to the increasing occurrence of natural disasters, the overuse of fertilizers and pesticides, and emerging threats such as plastic pollution[51]. Although the promulgated *Land Administration Law* stated a balanced system of arable land occupation and compensation, the issue of compensated arable land quality is usually much worse than the occupied land (inferior land compensated for excellent land occupied) remains difficult to solve[52]. Therefore, China's cultivated land area of 1,350,974 km^2 was quality grade based on 15 levels (1st grade the best and 15th grade the worst) in 2015 to promote arable land conservation[42]. In this study, China's cultivated land was divided into five categories according to the further classification by the MLR, rated as excellent quality land (Grade 1–4), good quality land (Grade 5–8), medium quality land (Grade 9–12), poor quality grade (Grade 13–14) and inferior quality land (Grade 15). Furthermore, we used ArcGIS 10.6 to extract the Chinese arable land 30 × 30 m raster data in 2020, with an overall classification accuracy of 88.90 ± 0.68%[53]. We then assigned grade values to new arable land from 2016 to 2020 according to the principle of a similar quality degree of neighboring units[54].

Evaluation of groundwater overexploitation. In this study, groundwater overexploitation of selected areas in China was delineated using the water level amplitude method[38] by comparing the *Shallow Groundwater Level Contours and the Burial Depth Atlas of China* of 1979 to that of 2011. The water level amplitude method refers to the evaluation of the groundwater exploitation of the mining area based on the survey data of the groundwater level in the initial year and the current year following the delineation standards in the *Guidelines for the Assessment of Groundwater Overexploitation Zones* (GBT34968-2017)[42]. The groundwater exploitation zoning was performed according to the following equation:

$$\mathrm{K} = (H_1 - H_2)/\mathrm{T} \quad (1)$$

where K is the average annual rate of groundwater level change (m a^{-1}), H_1 is the groundwater burial depth of the initial year (1979) (m), H_2 is the groundwater burial depth of the current year (2011) (m), and T = 33, is the period (a). According to the groundwater overexploitation zoning criteria, the areas where the average annual decrease rate of groundwater level change of $K < 0.3$ m a^{-1} represented the groundwater use is non-overexploitation (if $0 > K$, represented there was recharging of groundwater; if $0 < K < 0.3$ m a^{-1}, represented the groundwater use is in a balanced status of exploitation and recharge). For $0.3 < K < 0.5$ m a^{-1}, $0.5 < K < 0.8$ m a^{-1}, and $K > 0.8$ m a^{-1} were used as the mining and replenishment specified as "slight", "moderate", and "severe" overexploitation zone, respectively.

Delineation of ecological protection redlines (EPR). As of December 30, 2019, only 20 provinces (Supplementary Fig. 8) have announced ecological protection red lines (EPR), which cannot be directly overlapped to get the national EPR map. According to the *Guidelines for the Delineation of Ecological Protection Red Lines*[30], the Ministry of Ecology and Environment of China has been delineated according to the evaluation of ecosystem services (www.ecosystem.csdb.cn) and the environmental sensitivity[55] (Supplementary Note 3). More specifically, we considered water retention, soil conservation, and biodiversity maintenance based on the guideline when evaluating the importance of ecosystem services. Environmental sensitivity was evaluated based on the three indicators: land desertification, soil erosion, and rocky desertification (Supplementary Table 3). Where the value of one of these indicators exceeded the threshold, the whole ecosystem would face environmental problems[56].

The overlay analysis function of ArcGIS 10.6 was used to modify the spatial layout of the delineation of EPR with the published results of the current 20 provinces. In this study, the delineation of EPR was divided into three categories by using the "con" statement from the grid calculation tool in ArcGIS 10.6: (1) the first-class EPR, where ecosystem services are extremely important and the environmental sensitivity is extremely high, was determined through the "AND operations"; (2) the other areas of the cultivated land within the delineation of EPR were taken as the second-class EPR, was determined through the "OR operations"; and (3) the whole remaining cultivated land in China was considered as outside the delineation of EPR.

Constructing the spatial trade-offs model for fallow

Objective functions

(1) Maximizing pollution control benefit (RI_i): Controlling pollution and restoring cultivated land is important for promoting the sustainable use of cultivated land resources. Therefore, spatial trade-offs aim to maximize the benefits of cultivated land pollution control after implementing fallow. We use the human health risk evaluation model[57] which is comprised of a toxic response coefficient and the pollutant content in the soil to take regional pollution background, migration, and transformation of pollutants toxicity in the soil into account. Considering relative to adults, children exhibit increased susceptibility to some chemical exposures, the exposure parameters and doses were calculated focusing solely on children, which resulted in a systematic characterization of the non-carcinogenic or carcinogenic risk of farmland pollution to children[58,59]. Compare to carcinogenic risk, the human health effects of non-carcinogenic substances are not death, but a decrease in body function[57]. Therefore, our study uses the determined children's carcinogenic risk to represent the most urgent area needed to be fallowed to mitigate the pollution degree for ensuring human health and assumed that the concentrations of pollutants in the soil after fallow could be effectively reduced to the same with no carcinogenic risk area. The average daily exposure doses of the three pathways of ingestion (ADD_{ing}), inhalation (ADD_{inh}), and dermal adsorption (ADD_{derm}) were calculated (Supplementary Note 5). The carcinogenic risks of the three exposure pathways were calculated by equations as follows:

$$CR = ADD \times SF \tag{2}$$

$$CR_{T,i} = \sum(CR_{ing,i} + CR_{inh,i} + CR_{derm,i}) \tag{3}$$

where ADD is the average daily exposure dose (mg kg^{-1}—day); CR is the carcinogenic risk quotient; SF is the carcinogenic slope factor of the carcinogenic pollutant and the SF values for pollutants are provided in Supplementary Table 7; and $CR_{T,i}$ is the total carcinogenic risk quotient in cultivated land grid unit i. Among the 16 kinds of PAHs, three organic pollutants: benzo(a)pyrene (BaP), fluoranthene, and pyrene, are included in the Priority Pollutant List by the U.S. Environmental Protection Agency (USEPA). Among them, BaP is a strong carcinogenic agent[49]. Therefore, BaP was selected as the representative toxic organic pollutant and is used to assess the health risk of PAHs. Considering the bioavailability in the human body, the acceptable threshold of $CR_{T,i}$ was then defined as 1×10^{-5} based on the International Commission on Radiological Protection[60]. The larger value of $CR_{T,i}$, the more urgent is needed to implement fallow.

(2) Maximizing environmental protection benefit (EP_i): The primary objective of fallow land is to regulate grain production, and it has evolved into an important means to solve the food surplus problem and improve the agricultural environment[28]. The main purpose of fallow in China at the current stage should focus on relieving ecological pressure, promoting natural ecological restoration, and identifying the fragility of the cultivated land ecosystem. Therefore, another model goal of optimization is to determine the highest protection efficiency of ecosystem services in cultivated land. We assumed that after fallow, the quality grade of cultivated land could be restored to grade 8 *sensu* the MLR[42], which meets the lowest requirement for good quality (Grade 5–8) (as further explained above in the section "Quality grading of cultivated land"). Groundwater overexploitation could be restored to a balanced zone for mining and replenishment. Lastly, the cultivated land within EPR ranges could be restored to the land conditions the same as those outside the EPR ranges. The objective function can be represented by:

$$EP_i = \sum(Q_{x,i} + G_{x,i} + E_{x,i}) \tag{4}$$

where, EP_i is the benefit of environmental protection in cultivated land grid unit i, with values ranging from 0 to 29. The higher the value of EP_i, the more efficient the environmental protection benefit. Based on *the Environmental Protection Law of China*, EPR is regarded as the "lifeline" which must be protected in a strict and compulsorily way and the cultivated land within the delineation of EPR need to be "retired" directly or designated as "urgent-fallow zone"[61,62]. In addition, groundwater depletion is primarily due to water withdrawals for agricultural irrigation, which easily resulted in groundwater funnel areas and caused irreversible damage to the ecosystem[55]. Therefore, the weighing of $Q_{x,i}$, $G_{x,i}$ and $E_{x,i}$ is implicitly different in calculating the benefit for environmental protection when implementing fallow in these areas.

Specifically, $Q_{x,i}$ is the quality grade of cultivated land, with values ranging from 0-8, ranked as excellent quality land (0) <good quality land (2) <medium quality land (4) <poor quality grade (6) <inferior quality land (8); $G_{x,i}$ is the groundwater overexploitation value, with a value range from 0 to 9, ranked as the groundwater in a balanced status of exploitation and recharge (0) <slight overexploitation (3) <moderate overexploitation (6) <severe overexploitation (9); and $E_{x,i}$ is the level of EPR delineation using the natural classification method, with a value range from 0 to 12, ranked as outside the delineation of EPR (0) <the second-class EPR (6) <the first-class EPR (12). Here, we used the function of "Re-classification" on ArcGIS 10.6 to assign values to these raster layers of $Q_{x,i}$, $G_{x,i}$ and $E_{x,i}$ for taking the implicit weight into account, and then to map the spatial distribution of EP by using the "Raster Calculator".

(3) Minimizing fallow implementation cost (CT_i): The implementation of fallow system inevitably causes part of the cultivated land to be temporarily withdrawn from cultivation, resulting in a short-term reduction in grain production. At the same time, fallow has an impact on the livelihoods of participating farmers. Participating farmers must receive reasonable economic subsidies to compensate for economic losses and to boost the willingness to participate in fallow. The total cost associated with fallow implementation included mainly four parts: the amount of crop production capacity lost (P_i), financial subsidies to farmers (S_i), fallow matching funds (F_i), and management costs on cultivated land (M_i), which refers to the soil treatment fee during the period of fallow cultivated land, such as soil pollution remediation or ecological restoration of groundwater exploitation. The objective function can be expressed as:

$$CT_i = P_i + S_i + F_i + M_i \tag{5}$$

$$P_i = y_i * x_i \tag{6}$$

$$F_i = F_1 + F_2 + F_3 + F_4 + F_5 \tag{7}$$

$$M_i \rightarrow \langle PI|Q|G|E| \rangle \tag{8}$$

where P_i is the amount of crop production capacity lost per unit area, y_i is the grain yield per unit area, x_i is the crop planting income. Based on China's cultivated land distribution, crops planted in each region, and taking into account the various empirical methods in China (including double cropping, three cropping in two years, and triple cropping), the grain yield per unit area (y_i) were represented by spatial data on China's cultivated land production potential[63]. The average cash incomes from China's major grains (rice, wheat, and corn) in 2015–2020 were 0.195, 0.167, 0.177, 0.159, 0.167, and 0.195 USD kg^{-1} (100 USD = 660 CNY), respectively, as latest reported in the *Compilation of National Agricultural Product Cost-Benefit* (2021)[64]. The average income of these recent 6 years was taken as the crop planting income, $x_i = 0.177$ USD kg^{-1}.

An underpaid fallow subsidy would undoubtedly greatly impact the income of farmers and reduce the willingness of farmers to participate in fallow cultivated land. Assuming that farmers are rational economic agents, and given the principle of voluntary fallow implementation policy in China, farmers will prefer to let their arable lands fallow when the financial subsidy for fallowing is equal to or higher than the transfer rent of cultivated land. To incentive farmers' willingness to fallow, our study adopted the price regionalization of cultivated land transfer (Supplementary Fig. 11) in China as the financial subsidy to farmers (S_i), which fully considered the differences in both socioeconomic development levels of each county and the quality grading of cultivated land[65]. During the fallow process, the fallow matching funds are needed for working expenses and increasing the fertility of soil. Based on the survey data from the national fallow pilot area, Shilin County, Yunnan Province[66], we identified the fallow matching funds, $F_i = 382.5$ USD hm^{-2}, consisting of five parts: technical training fees (F_1 =34.1 USD hm^{-2}), the amount of information and data services ($F_2 = 10.9$ USD hm^{-2}), the grant fee for green manure and seed ($F_3 = 51.1$ USD hm^{-2}), the fee for mechanical shredding and field return of green manure ($F_4 = 204.5$ USD hm^{-2}), and microbiological applications (F_5 =81.8 USD hm^{-2}). For the management costs on cultivated land (M_i), our study proposes differentiated costs and corresponding fallow modes (Supplementary Table 8) based on the degrees of four eco-environmental stressors for cultivated land, which is fully aligned with national requirements specified in *the Pilot Program on Exploring Implementation of Cultivated land Crop Rotation and Fallow System in 2019* was released[6]. Specifically, for soil pollution remediation, we collected common hyperaccumulator plants' costs for remediation of soil heavy metals pollution in China, which included the detailed labor cost and expenses on production materials such as compound fertilizer, urea, and pesticide use (Supplementary Table 9).

Multi-criteria optimization algorithm. A multi-criteria optimization algorithm based on the objective functions was used to determine the priority area of fallow in China[16]. This allowed for defining the areas of cultivated land to be fallowed in each planning unit, aiming to minimize cost (the total cost of fallow implementation) and/or maximize benefit (the pollution control benefit and/or the environmental protection benefit):

$$\max or \min \left(\frac{w_r RI_{s,i} + w_e EP_{s,i}}{CT_{s,i}} \right) \tag{9}$$

$$subject\ to \frac{\sum_i^{n_p} x_i}{S_{total}} \leq 100\% \tag{10}$$

$$RI_{s,i} = (CR_{T,i} - CR_{T,\min})/(CR_{T,max} - CR_{T,\min}) \tag{11}$$

$$CR_{T,\min} = 1 \times 10^{-5} \tag{12}$$

$$EP_{s,i} = (EP_i - EP_{\min})/(EP_{max} - EP_{\min}) \tag{13}$$

$$CT_{s,i} = (CT_i - CT_{\min})/(RI_{max} - CT_{\min}) \tag{14}$$

where x is the decision variable representing the proportion of a controlling factor's type to be fallowed within each cultivated land grid unit i. and n_p is the total number of cultivated land grid units being fallowed. If there is no fallow scale constraint, the maximum fallow area could be up to 100% of the total cultivated area in China (S_{total}) and fallow "problematic cultivated land" as much as possible. $CT_{s,i}$ is the total cost of fallow implementation for the cultivated land grid unit i *after standardization*. The other two components of the objective function, $RI_{s,i}$ and $EP_{s,i}$ represent, respectively, the pollution control benefit and the environmental protection benefit of cultivated land grid unit i *after standardization*. Here, $RI_{s,i}$ is calculated based on the total carcinogenic risk quotient ($CR_{T,i}$). We set $CR_{T,\min}$ as 1×10^{-5} based on the acceptable threshold and bioavailability in a human body[60]. The user-defined parameters w_r and w_e, weigh the relative contributions of the pollution control and environmental protection components, respectively, to the objective function. They are required because the equivalence of objectives with different units is a subjective decision that must be made by decision-makers. In addition, alternative scenarios simulation required components removal of this model's objective function, such as removing the total cost of fallow implementation (CT_i) to maximize fallow benefits without considering the cost.

(1) Fallow scale constraints: There is a need to determine the demand for cultivated land in China under the constraint of food security aimed at maximizing the fallow period at the national level without negative impacts on the threshold of national food security. Although it is not possible to avoid upsetting the balance of China's grain supply and demand in the long term[67], it is important to ensure moderate food self-sufficiency as the upper limit of China's fallow period. China is currently advancing towards intensive and environmentally friendly agriculture and therefore, high-tech agricultural products such as cultured meat and vertical agriculture are pursued vigorously. Meanwhile, China could rely on the favorable conditions of the global market and the strategic advantages of the Belt and Road Initiative to deepen trade cooperation of agricultural products which would alleviate the pressure on domestic cultivated land resources and the agricultural production environment. Furthermore, the definition of fallow in the current pilot program is not limited to land "rest" without land productivity in a long fallow (10–15 years fallow). In this study, 20% of the total cultivated area in China (S_{total}) was categorized as the upper limit of flexible and ideally fallow areas in China ($\triangle CL$).

$$subject\ to \frac{\sum_i^{n_p} x_i}{S_{total}} = A_i \leq \triangle CL \tag{15}$$

$$\triangle CL \rightarrow 20\% \rightarrow \langle \varepsilon_1 | \varepsilon_2 | \cdots | \varepsilon_n | \rangle \tag{16}$$

where A_i is the total area of cultivated land to be fallowed and the constraint makes the proportion of the cultivated land fallowed limits to a maximum value of $\triangle$CL = 20%. To ensure national food security and successful implementation of fallow, the value of $\triangle$CL is consistent with the recommendations of previous studies[33,34], which considered multi-factors of ε, such as urbanization rate and grain yield per unit cultivated area. According to Jun Han, deputy director of the Central Leading Group for Financial and Economic Affairs, "a lower limit of 79.0% (107.2×10^4 km^2) of total cultivated land is required to maintain a self-sufficiency rate of 85%, and a lower limit of 83.9% (113.9×10^4 km^2) is required to maintain a self-sufficiency rate of 90%"[33]. By conducting a national survey on the impact of urbanization on food consumption, Jun Han's assumption mainly considered the growing urbanization rate, population growth, and changing food consumption structure. Furthermore, Yu et al.[34] constructed a prediction model, which considered population, grain consumption per capita, and grain yield per unit cultivated area. Based on the moderate self-sufficiency bottom line of "100% demand of rations and 90% of other food consumption", Yu et al.[34] showed that China's cultivated land demand would drop from 84.4% (114.5×10^4 km^2) to 76.4% (103.7×10^4 km^2) from 2025 to 2035.

(2) Scenario simulation: Five fallow scenarios have been set up nationwide:

Scenario 1, priority to risk mitigation scenario (hereafter "PMS"), solely focuses on the objective function of maximizing pollution control benefit (RI$_i$). PMS targets serious pollution of the topsoil of cultivated land in China, which is a threat to human health, especially in the severely polluted area caused by heavy metals, organic pollutants, and PAHs due to the abuse of chemical fertilizers.

Scenario 2, priority to ecological civilization scenario (hereafter "PES"), solely focuses on the objective function of maximizing environmental protection benefit (EP$_i$). PES targets to alleviate the conflict between cultivated land use and ecological conservation, as the practice of continuous land cultivation could cause a sharp decline in the quality of cultivated land and ecosystem due to overexploitation of groundwater.

Scenario 3, cost reduction scenario (hereafter "CRS"), solely focuses on the objective function of minimizing fallow implementation cost (CT$_i$). CRS was designed to minimize the reduction in food production due to fallow implementation and relieve pressure off state financial expenditures, such as the compensation fee to farmers and remediation cost on soils contaminated with pollutants.

Scenario 4, multiple benefits scenario (hereafter "MBS"), both focus on the objective function of maximizing pollution control benefit (RI$_i$) and maximizing environmental protection benefit (EP$_i$), but without considering the fallow implementation cost. These two objective functions can be solved over a range of relative weights to understand how the two components trade-off in MBS. Here, as this scenario focuses on the scale and layout of fallow priority on a macro scale, a uniform weight, $w_r = w_e = 0.5$, was designed in scenario 4 and scenario 5 to address the fallow benefits trade-off between RI$_i$ *and* EP$_i$.

Scenario 5, comprehensive fallow scenario (hereafter "CFS"), deals with three objectives altogether, expected to achieve the objective function of maximizing pollution control benefit (RI$_i$) and maximizing environmental protection benefit (EP$_i$), while minimizing fallow implementation cost (CT$_i$) to decrease fiscal expenditure.

Data availability

The authors declare that the data supporting the findings of this study are available within the article and its Supplementary Information (see also "Methods"). The data of 5597 samples from 1781 soil sites in cultivated land for the soil pollution assessment are referred to Zeng et al. (2019) (https://doi.org/10.1016/j.scitotenv.2019.05.291). The current Chinese cultivated land cover is from Resource and Environment Science and Data Center (https://www.resdc.cn/). The raw data of the Shallow Groundwater Level Contours and the Burial Depth Atlas of China of 1979 to that of 2011 are available in the China Geological Survey (https://www.cgs.gov.cn/) and the Groundwater Information Application Service System (https://jcgc.cigem.cn/dataShare/). The original data sources used for delineating the ecological protection redlines (EPR) and fallow implementation cost calculation are summarized and available in https://github.com/Camellia-Ch/NCEE.

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References

1. Tilman, D. et al. Agricultural sustainability and intensive production practices. *Nature* **418**, 671–677 (2002).
2. Braun, V. J. Strategic body needed to beat food crises. *Nature* **465**, 548–549 (2010).
3. Khan, S. et al. Global soil pollution by toxic elements: current status and future perspectives on the risk assessment and remediation strategies—a review. *J. Hazard Mater.* **417**, 126039 (2021).
4. Tamburini, G. et al. Agricultural diversification promotes multiple ecosystem services without compromising yield. *Sci. Adv.* **6**, 45 (2020).
5. Wanger, T. C. et al. Integrating agroecological production in a robust post-2020 Global Biodiversity Framework. *Nat. Ecol. Evol.* **4**, 1150–1152 (2020).
6. MARA of China (Ministry of Agriculture and Rural Affairs of China). Notice on doing a good job in the pilot work of the Cultivated Land Rotation and Fallow System in 2019. http://www.zzys.moa.gov.cn/zcjd/201906/t20190625_6319177.htm (2019).
7. Shi, K., Yang, Q., Li, Y. & Sun, X. Mapping and evaluating cultivated land fallow in Southwest China using multisource data. *Sci. Total Environ.* **654**, 987–999 (2019).
8. Wu, Q. & Xie, H. A review and implication of land fallow system research. *J. Resour. Ecol.* **8**, 223–231 (2017).
9. Gumma, M. K. et al. Mapping rice-fallow cropland areas for short-season grain legumes intensification in South Asia using MODIS 250 m time-series data. *Int. J. Digit. Earth* **9**, 981–1003 (2017).
10. Krishna, G. M. et al. Mapping cropland fallow areas in Myanmar to scale up sustainable intensification of pulse crops in the farming system. *Gisci. Remote Sens.* **1**, 924–949 (2018).
11. Deng, X., Huang, J., Rozelle, S. & Uchida, E. Cultivated land conversion and potential agricultural productivity in China. *Land Use Policy* **23**, 372–384 (2006).

12. Liu, J. & Diamond, J. China's environment in a globalizing world. *Nature* **435**, 1179–1186 (2005).
13. Cui, K. & Shoemaker, S. P. A look at food security in China. *NPJ Sci. Food* **2**, 4 (2018).
14. Zhang, B., Wang, B. & Hughes, R. C. China should track impact of pollution on health and the environment. *Nature* **592**, 507 (2021).
15. Zhao, Q. et al. *Research on Cultivated Land Rotation and Fallow System in China* (China Sci Press, 2019).
16. Lu, H. et al. Determinants of cultivated land recuperation in ecologically damaged areas in China. *Land Use Policy* **81**, 160–166 (2019).
17. Halpern, B. S. et al. Achieving the triple bottom line in the face of inherent trade-offs among social equity, economic return, and conservation. *Proc. Natl Acad. Sci. USA* **110**, 6229–6234 (2013).
18. Erb, K.-H. et al. Exploring the biophysical option space for feeding the world without deforestation. *Nat. Commun.* **7**, 11382 (2016).
19. Mappin, B. et al. Restoration priorities to achieve the global protected area target. *Conserv Lett.* **12**, e12646 (2019).
20. Strassburg, B. B. N. et al. Global priority areas for ecosystem restoration. *Nature* **586**, 724–729 (2020).
21. Lu, J., Wang, Z. & Yang, J. Exploring a moderate fallow scale of cultivated land in China from the perspective of food security. *Int. J. Env. Res. Public Health* **16**, 4329 (2019).
22. Huang, G. & Zhao, Q. A discussion on land fallow rotation problem. *Ecol. Environ. Sci.* **26**, 357–362 (2017).
23. Liang, X. et al. China's resilience-space for cultivated land protection under the restraint of multi-scenario food security bottom line. *Acta Geogr. Sinica* **77**, 697–713 (2022).
24. Xun, G., Song, Y. & Cheng, X. Impacts of the land fallow and crop rotation practice on grain security in China and solutions. *Res. Agric. Mod.* **38**, 73–88 (2017).
25. Wang, L., He, P. & Wei, J. Research on fallow scale of cultivated land based on national food security strategy. *Agric. Econ.* **07**, 78–80 (2018).
26. Yang, Q. et al. Does fallowing cultivated land threaten food security? Empirical evidence from Chinese pilot provinces. *Sustainability* **11**, 2836 (2019).
27. Xie, H., Wang, W. & Zhang, X. Evolutionary game and simulation of management strategies of fallow cultivated land: a case study in Hunan province, China. *Land Use Policy* **71**, 86–97 (2018).
28. GOV of China (People's Government of China). Opinions on Accelerating Agricultural and Rural Modernization by Comprehensively Promoting Rural Revitalization. http://www.gov.cn/zhengce/2021-02/21/content_5588098.htm (2021).
29. State Council of China. Opinions of the State Council on Strengthening Key Environmental Protection Work (Guo Fa 2011 No. 35). http://www.gov.cn/zwgk/2011-10/20/content_1974306.htm (2011).
30. MEE of China (Ministry of Ecology and Environment of China). Guidelines for the Delineation of Ecological Protection Red Lines. http://www.mee.gov.cn/gkml/hbb/bgt/201707/t20170728_418679.htm (2017).
31. Yang, Q., Chen, Z., Xin, G. & Zeng, L. The historical evolution of Chinese cultivation system and some thoughts on the current land fallow and crop rotation policy. *West Forum* **28**, 1–8 (2018).
32. Tan, S., Han, S. & Zhang, L. Study on fallow scale and dynamical simulation of major grain producing areas in China from the food security perspective. *China Land Sci.* **34**, 9–17 (2020).
33. Han J. Keep the red line of arable land, the staple food problem cannot rely on foreign countries. http://finance.sina.com.cn/hy/20140428/170318949199.shtml (2014).
34. Yu, H. et al. Forecast on China's cultivated land protection baseline in the new era by multi-scenario simulations. *Resour. Sci.* **43**, 1222–1233 (2021).
35. Shi, F., Yang, Q., Wang, C. & Chen, Z. Practice and research progress on spatio-temporal collocation of fallow of cultivated land in world. *Transact. CSAE* **34**, 1–9 (2018).
36. Luo, T. & Zou, X. Design of translation mechanism among uncultivated, abandoned land, reforestation land and fallow. *West Forum* **25**, 40–46 (2015).
37. Xiao, D. et al. Impact of alternative cropping systems on groundwater use and grain yields in the North China Plain Region. *Agr. Syst.* **153**, 109–117 (2017).
38. Xie, H., Cheng, L. & Lu, H. Farmers' responses to the winter wheat fallow policy in the groundwater funnel area of China. *Land Use Policy* **73**, 195–204 (2018).
39. Zeng, S. et al. Assessing the spatial distribution of soil PAHs and their relationship with anthropogenic activities at a national scale. *Int. J. Env. Res. Public Health* **16**, 4928 (2019).
40. Zeng, S. et al. Spatial assessment of farmland soil pollution and its potential human health risks in China. *Sci. Total Environ.* **687**, 642–653 (2019).
41. Duan, J. et al. Consolidation of agricultural land can contribute to agricultural sustainability in China. *Nat. Food* **2**, 1014–1022 (2021).
42. The Ministry of Land and Resources (MLR). Cultivated land quality grade evaluation of China. http://www.mnr.gov.cn/dt/bwdt/201412/t20141219_2355077.html (2015).
43. The Hydrogeological Survey Center of China Geological Survey (CGS). The 2011 shallow groundwater level contours and burial depth atlas. http://www.cgs.gov.cn/ (2012).
44. The Department of International Cooperation, science and Technology. Guidelines for the assessment of groundwater overexploitation zones (GBT34968-2017). http://zwgk.mwr.gov.cn/jsp/yishenqing/appladd/biaozhunfile/detail.jsp?bzbh=GB%252FT%2B34968-2017 (2017).
45. The Department of Water Resources of the Ministry of Water Resources. *Development and Utilization of Groundwater Resources in China at the Beginning of the 21st Century* (China Water Conservancy and Hydropower Press, 2004).
46. Zhang, Z. & Li, L. *The Atlas of Groundwater Resources and Environment in China* (Sinomap Press, 2006).
47. MEE of China (Ministry of Ecology and Environment of China). National ecological protection red line delineation is basically completed. http://www.mee.gov.cn/ywdt/spxw/202107/t20210707_845785.shtml (2021).
48. MEE of China (Ministry of Ecology and Environment of China). Soil environmental quality risk control standard for soil contamination of agricultural land: GB15618-2018. http://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/trhj/201807/t20180703_446029.shtml (2018).
49. Maliszewska-Kordybach, B. Polycyclic aromatic hydrocarbons in agricultural soils in Poland: preliminary proposals for criteria to evaluate the level of soil contamination. *Appl. Geochem.* **11**, 120–127 (1996).
50. China Geological Survey. Technical requirements for regional ecosystem geochemistry assessment (DD2005-02). http://www.mnr.gov.cn/gk/bzgf/201005/t20100531_1971751.html (2005).
51. MacLeod, M. et al. The global threat from plastic pollution. *Science* **6550**, 61–65 (2021).
52. Hu, Y. et al. Food production in China requires intensified measures to be consistent with national and provincial environmental boundaries. *Nat. Food* **1**, 572–582 (2020).
53. Gao, Y. et al. Consistency analysis and accuracy assessment of three global 30-m land-cover products over the European Union using the LUCAS dataset. *Remote Sens.* **12**, 3479 (2020).
54. Song, W. & Pijanowski, B. C. The effects of China's cultivated land balance program on potential land productivity at a national scale. *Appl. Geogr.* **46**, 158–170 (2014).
55. Liu, J. et al. Evaluation of ecological sensitivity in China. *J. Nat. Resour.* **30**, 1607–1616 (2015).
56. Bai, Y. et al. Developing China's Ecological Redline Policy using ecosystem services assessments for land use planning. *Nat. Commun.* **9**, 3034 (2018).
57. U.S. Environmental Protection Agency (USEPA). *Environmental protection agency. Guidelines for Human Exposure Assessment*. (EPA/100/B-19/001) Washington, D.C, Risk Assessment Forum, U.S. EPA (2019).
58. Ali, N. et al. Endocrine disrupting pesticides in soil and their health risk through ingestion of vegetables grown in Pakistan. *Environ. Sci. Pollut. R* **26**, 8808–8820 (2019).
59. Wang, C., Zhou, S., Song, J. & Wu, S. H. Human health risks of polycyclic aromatic hydrocarbons in the urban soils of Nanjing, China. *Sci. Total Environ.* **612**, 750–757 (2018).
60. Chen, H. et al. Source apportionment and health risk assessment of trace metals in surface soils of Beijing metropolitan, China. *Chemosphere* **144**, 1002–1011 (2016).
61. MEE of China (Ministry of Ecology and Environment of China). The Environmental Protection Law of the People's Republic of China in 2015. https://www.mee.gov.cn/ywgz/fgbz/fl/201404/t20140425_271040.shtml (2014).
62. Wang, X. et al. Protection effect and vacancy of the ecological protection redline: a case study in Guangdong–Hong Kong–Macao Greater Bay Area, China. *Remote Sens.* **13**, 5171 (2021).
63. Liu, L., Xu, X. & Chen, X. Assessing the impact of urban expansion on potential crop yield in China during 1990–2010. *Food Secur.* **7**, 33–43 (2015).
64. National Bureau of Statistics of China. *China Statistical Yearbook* (China Statistical Press, 2019).
65. Qi, Y. et al. Establishment and verification of the regionalization of cultivated land price in China. *Transact. CSAE* **7**, 250–257 (2021).
66. Chen, Z. & Yang, Q. Study on the implementation of crop rotation and fallow system in Guangxi. *Guihai Tribune* **34**, 69–76 (2018).
67. Gu, B. et al. Four steps to food security for swelling cities. *Nature* **566**, 31–33 (2019).

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Author contributions

S.Z.: formal analysis, methodology, data curation, writing, and investigation. F.C.: conceptualization, methodology, validation, supervision, and funding acquisition. G.-j.L.: rewriting-review and editing and validation. E.R.: rewriting-review. T.C.W.: rewriting-review and editing and supervision.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Fu Chen or Thomas Cherico Wanger.

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