

# Spatial-temporal change in urban agricultural land use efficiency from the perspective of agricultural multi-functionality: A case study of the Xi'an metropolitan zone

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**Abstract:** The excessive expansion of urbanized areas has resulted in haphazard land utilization, immoderate consumption of superior agricultural land and water resources, significant fragmentation of agricultural landscape, and gradual deterioration of the agro-ecological environment. Combined, these factors cause poor land use efficiency. Under these circumstances, comprehensively assessing land use efficiency for urban agriculture is a key issue in land use research. Currently, evaluation methods for agricultural land use efficiency narrowly concentrate on aspects of economic input and output. However, urban agro-ecosystems can provide diverse economic, social, and ecological services and functions. In particular, the social and ecological services and functions originating from agricultural land, which have a higher value than economic services, play a significant role in ensuring regional social, ecological, and environmental security. However, recent research has rarely taken these benefits into consideration. Therefore, land use value has been greatly underestimated, which has resulted in mishandled and poor land use policies. In this study, we apply Landsat imagery and social and economic statistical data for the Xi'an metropolitan zone (XMZ) to investigate agricultural multi-functionality. We develop an evaluation framework for urban agricultural land use efficiency and identify agro-ecosystem services and functions as important outputs from agricultural land. The land use efficiency of urban agriculture is then evaluated using ecosystem services models, providing a mechanism for assessing spatial-temporal changes in land use efficiency in the XMZ from 1999 to 2015. Four important conclusions are reached from this analysis. First, the rapid urbanization and agricultural transformation from traditional cereal cultivation to modern urban agriculture has resulted in steadily increasing costs, outputs, and land use efficiency of urban agriculture. The total output value increased 41% and land use efficiency per hectare increased by 33.13% on average. Second, the spatial patterns of comprehensive output and land use efficiency were dominated by economic outputs from agricultural land. Areas near cities, which are dominated by orchard and arable land, provide

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more economic functions. These areas support and regulate services due to the transformation from extensive cereal production to intensive modern urban agriculture; therefore, they have higher output value and land use efficiency. In contrast, areas distant from cities, towns, and high traffic roads, namely, remote rural areas, provide more support and regulating services, but have relatively lower economic function due to inaccessibility to urban markets and slow agricultural transformation. Therefore, these areas have lower output value and land use efficiency. The spatial change in agricultural output and land use efficiency in urban areas is strongly dependent on the degree of urbanization and agricultural transformation. Third, the total output value and land use efficiency of urban agriculture measured with our approach are much higher than evaluations using traditional methods. However, the spatial patterns measured using the two approaches are in agreement. The evaluation framework integrates ecological services and economic and social functions into a comprehensive output from agricultural land. This approach is more methodical and accurate for evaluating the comprehensive efficiency of land use based on quantities and spatial scale because they are at the pixel scale. Finally, the evaluation results have important implications for enhancing current agricultural subsidies and even implementing ecological payment policies in China. Most importantly, they can be directly applied to agricultural transformation regulations, decision-making, and guidance for rational land utilization.

**Keywords:** urban agriculture; land use efficiency; agro-ecosystem services; agricultural multi-functionality; Xi'an metropolitan zone (XMZ)

## 1 Introduction

The agro-ecosystem is a key terrestrial ecosystem that provides ecosystem services to society. In the cultivated and rapidly urbanizing areas of China, the haphazard utilization of urban land, immoderate consumption of farmland and water bodies, gradual fragmentation of the agricultural landscape, and serious ecological deterioration have led to a significant decrease in agricultural land use efficiency. Researching these factors, particularly in areas impacted by urbanization, can optimize regional agricultural land use (Peng *et al.*, 2005).

Land use efficiency has traditionally been analyzed using economic efficiency, and primarily focused on economic intensification of land use and its spatial differentiation (Jiang and Diao, 2008; Yang *et al.*, 2009; Liang *et al.*, 2013). Most scholars applied the data envelopment analysis (DEA) model; urban lands were taken as the decision-making units (DMU) to develop the input and output indicators, but the actual land types used for inputs and outputs were not distinguished (Song and Gao, 2008; Gong *et al.*, 2011; Toma *et al.*, 2015;). In fact, due to diverse land resource functions, land use efficiency is essentially a comprehensive efficiency that integrates economic, social, and ecological outputs generated from agricultural land (Luo and Wu, 2003; Cao *et al.*, 2006; Fang *et al.*, 2013; Zhang *et al.*, 2015). Therefore, confronting gradually emerging environmental and ecological problems, some scholars have taken ecological and social effects into account when evaluating land use efficiency (Chen *et al.*, 2007; Zhang, 2014). However, this type of evaluation of ecological efficiency, especially for urban land use, merely adopts the forest coverage rate, “three wastes” emissions (waste gas, waste water, and industrial residue), and green space as proxy indicators (Peng *et al.*, 2005; Ye *et al.*, 2008). This evaluation neglects the observation that the urban agro-ecosystem provides multiple ecological services and functions to economic, social, and ecologically sustainable urban development. These proxies are unable to thoroughly express the ecological outputs, and also cannot describe the social functions of

land use. Therefore, developing a scientific evaluation method to determine urban agricultural land use efficiency is one of the key issues in land use research.

Currently, evaluating agricultural land use efficiency concentrates on economic input and output, and the social and ecological services and functions provided by the agro-ecosystem are rarely taken into consideration. However, some studies indicated that their value is much higher than the economic output (Chabi-Olaye *et al.*, 2005; Lewandowski and Schmidt, 2006; Getachew *et al.*, 2006, 2008; Peng *et al.*, 2013; Toma *et al.*, 2015). Because the traditional evaluation concept narrowly focuses on the economic output, the corresponding subsidy policies related to agricultural production and restructuring policies, and investment policies have resulted in a decrease in agricultural comparative efficiency. Furthermore, these policies have led to poor morale among Chinese farmers, an unwillingness of farmers to invest in agriculture, and the subsequent abandonment of arable land, soil contamination, and degradation. Therefore, the traditional evaluation of agricultural land use efficiency, which omits the significant social and ecologic services and functions, ultimately are not objective and harm the policies for rational use of agricultural land.

The agro-ecosystem has multiple functions (Schipanski *et al.*, 2014), and social and ecological services and functions are major outputs from agricultural land that play significant roles in ensuring regional social, ecological, and environmental security (Wang and Zhou, 2014; Johnson *et al.*, 2016). Urban agro-ecosystems provide fundamental ecological regulation and support services, which benefit society. However, at present, output studies do not fully consider the multi-functionality of urban agriculture; ecological services and social functions are generally omitted. Thus, it is necessary to integrate the service and function benefits provided by agricultural land into evaluating land use efficiency.

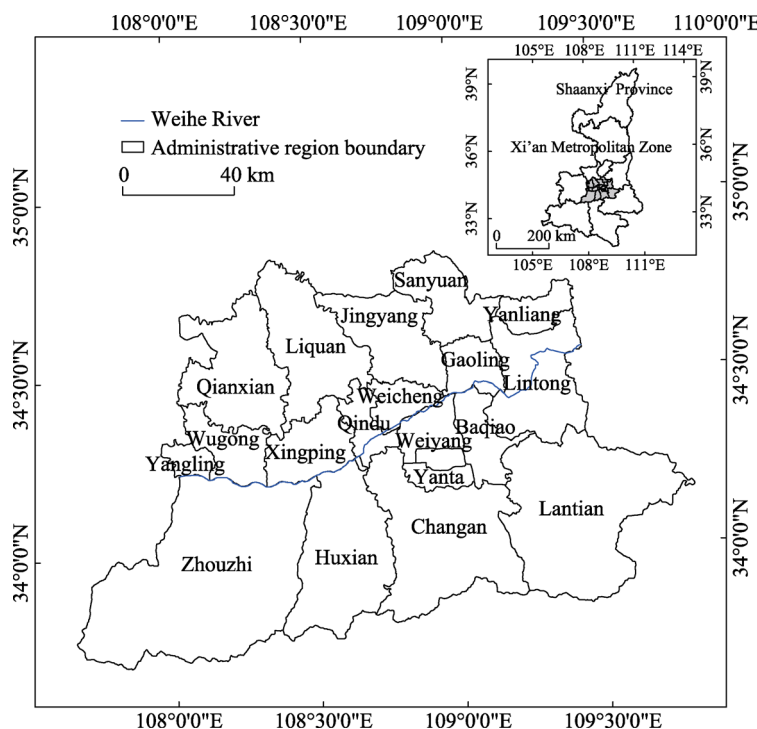
This study uses the Xi'an metropolitan zone as a case study to evaluate land use efficiency from an agricultural multi-functionality perspective, and incorporates agro-ecosystem services and functions as land outputs. The study area is highly cultivated and strongly affected by rapid urbanization, making it an ideal location for this evaluation. The primary objectives of the study are as follows. First, we develop a comprehensive evaluation framework and methods for land use efficiency by identifying the urban agro-ecosystem provisioning and regulation services considering diverse urban agricultural outputs and inputs. Second, we assess the comprehensive value of agro-ecosystem outputs by applying total input values, including the cost of natural resources, to a newly developed ecosystem services evaluation method. Finally, we evaluate the comprehensive efficiency and spatial changes in agricultural land use in the XMZ.

This study provides a new perspective for objectively understanding the outputs from urban agriculture and a comprehensive evaluation framework for agricultural land use efficiency. This work can aid in improving agricultural subsidy policies and policy-making associated with sustainable development in urban and rural areas.

## 2 Research area and data

### 2.1 Research area

The Xi'an metropolitan zone (XMZ) is an urban agglomeration area in central Guanzhong Plain in Northwest China (Figure 1). It administratively includes Xi'an city, part of Xian-



**Figure 1** The Xi'an metropolitan zone (XMZ)

yang city, and the Yangling agricultural high-tech industry demonstration zone. The total area is approximately 14,985 km<sup>2</sup>, mainly comprising the Weihei loess tableland, Weihe alluvial plain, and southern Qinling Mountains. The cultivated northern plain area is flat with altitudes varying from 335 m to 660 m above sea level, and the forested southern area is steep with an elevation of over 1200 m. The XMZ has an average temperature of 26°C in July, with a warm, temperate, semi-humid continental monsoon climate. The average annual rainfall ranges from 522.4 to 719.5 mm, and more than 80% of the precipitation falls in the crop-growing season. The dominant soil types from the northern plain and south to the Qinling Mountains are yellow cinnamon soil, cinnamon soil, yellow brown soil, and brown soil. Although the agricultural region is arid, irrigation canals are well developed, and irrigated fields account for an estimated 72.39% of the total arable land. Therefore, the XMZ has historically been an important grain-producing region for Northwest China. The XMZ, with a high population density and high economic activity, is the most important urban agglomeration area and core zone for socio-economic development in Shaanxi Province and Northwest China. At present, the region's fruit production, dairy farming, and grain production are most significant within China, hence one of the main temperate fruit production centers. The output value of the agricultural sector was over 3.9×10<sup>10</sup> yuan in 2015, which accounted for almost 30% of the total output value of Shaanxi Province. The XMZ has a production system that primarily consists of food, vegetables, fruits, breeding livestock, and processed agricultural products. Furthermore, the transformation from traditional agriculture to a modern agricultural system is ongoing, and represents the modernization and diversification of urban agriculture.

In addition to agricultural modernization and diversification, the quantities and types of agricultural inputs and outputs have also undergone tremendous changes. Under rapid urbanization and agricultural transformation, the occupation and conversion of agricultural land, decrease in agricultural comparative efficiency, degradation of arable land, and low farmer morale have emerged as serious issues, which have caused the abandonment of arable land and extensive use of fertile farmland. Currently, with the diversification of urban agriculture, the proportion of the social and ecological services in total agricultural output has risen significantly. Therefore, the traditional evaluation results, which have neglected the social and ecological functions of agriculture and underestimated agricultural benefits and land use efficiency, have strongly and negatively influenced agricultural development and agricultural policy-making. It is necessary to evaluate land use efficiency covering all social and ecological services, and improve society’s awareness of agro-ecosystem services and functions. From a policy perspective, this will gain the government’s attention, address the social and ecological outputs from agriculture, and utilize economic instruments to encourage farmers’ enthusiasm and improve land use efficiency.

2.2 Data

Land-use data were obtained from Landsat Thematic Mapper (TM) images from 1999 and 2006 and Operational Land Imager (OLI) images from 2015 (<http://earthexplorer.usgs.gov/>). These data were combined with a land use map, vegetation type map for the XMZ, and field investigation data (Figure 2). The population data was collected from the sixth national census of 2010. The agricultural survey data and related socio-economic data were extracted from *Xi’an Statistical Yearbook* in 2000, 2007, and 2015 (XSBM, 2000; XSBM, 2000;

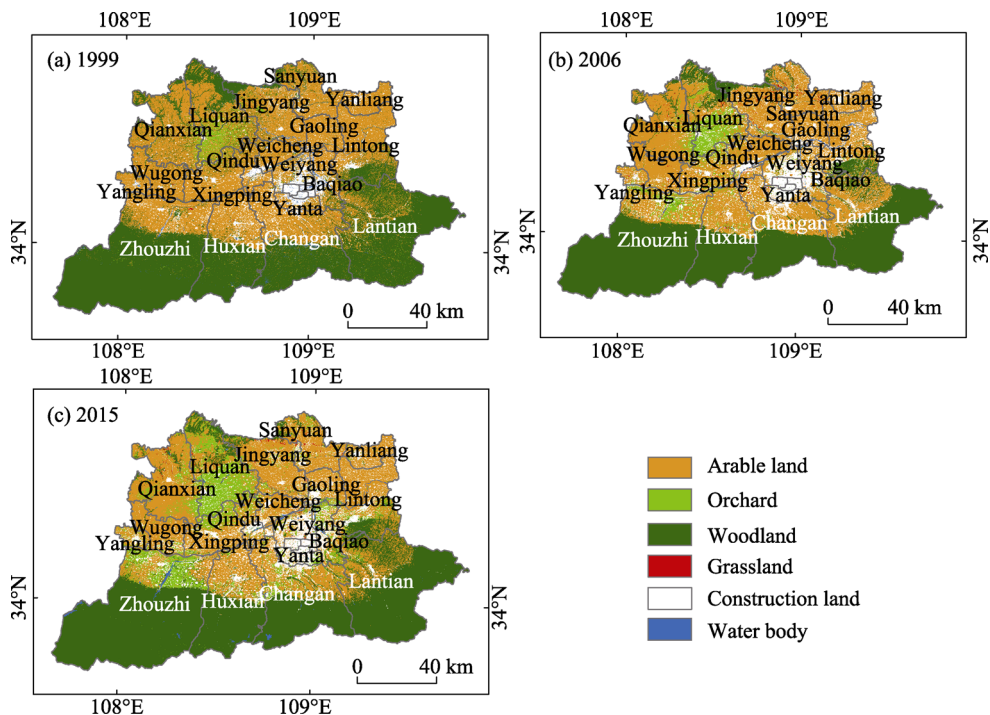


Figure 2 Land use in the Xi’an metropolitan zone from 1999 to 2015

XSBM, 2016) and *Xianyang Statistical Yearbook* in 1999, 2006 and 2015 (XYMBS, 1999; XYMBS, 2005; XYMBS, 2015). We also acquired information from *National Agricultural Product Assembly of Profit and Cost* in 2005 and 2015 (NDRCP, 2005; NDRCP, 2015).

### 3 Research framework and methods

#### 3.1 Research framework

Because the overall ecosystem services delivered by an agro-ecosystem can improve human welfare, from an agricultural multi-functionality perspective, we regard these services and functions as outputs from agricultural land. We extend the output items from the traditional economic production (namely economic function) to social and ecological services and functions, and propose a comprehensive evaluation framework for agricultural land use efficiency. The new framework includes a number of assessment processes:

- First, we analyze the characteristics of a specific agro-ecosystem and identify the main agro-ecosystem services or functions, incorporating ecological, social, and economic services or functions.
- We determine the output indicators of agricultural land described by agro-ecosystem services and the actual cost of items in agricultural activity.
- Models are built to measure the values of the main output and input indicators and calculate the agricultural land use efficiency at a pixel scale.
- The changes in agricultural outputs, inputs, and land use efficiency are spatial-temporally analyzed using a spatial analysis model.

This research framework is an open evaluation approach; when we determinate the output and input indicators, we consider the specific agricultural type and agricultural activities in a specific region. These indicators describe the main outputs from agricultural land and critical issues for sustainable development, both regionally and agriculturally.

#### 3.2 Indicators

We constructed an input and output index of urban agricultural land and built a comprehensive land use efficiency accounting framework based on economic, social, and ecological services. Agricultural production inputs included seeds, fertilizers, pesticides, plastic film, labor, and agricultural machinery; water consumption was also included in dry farming areas. In view of the multi-functionality of agriculture, most urban agro-ecosystem services and functions were incorporated and regarded as the outputs from agricultural land, including food and raw production, hydrological regulation, climate regulation, carbon sequestration, oxygen release, biodiversity protection, nitrogen cycle regulation, soil and water conservation, weed and pest control, beneficial insect protection (Meagan *et al.*, 2014), water purification and waste treatment, and aesthetic creation (Sieber and Pons, 2015) (Table 1).

The agricultural development in the XMZ is dominated by farming, fruit production on the plains, and forestry in the southern mountains. Therefore, considering the various geographical features, characteristics of agricultural development, and data availability, we selected nine main services or functions as indicators representing the total output of urban agricultural land in this study. These indices incorporated economic production,

**Table 1** Evaluation indicators of agricultural land use efficiency

Item	Indicators	Description of the variables
Costs (Input)	Fertilizer	Fertilizer cost
	Agricultural plastic film	Plastic film cost
	Agricultural pesticide	Pesticide cost
	Total power of agricultural machinery	Energy cost of agricultural machinery
	Labor	Labor cost for planting and managing crop
	Water resource	Water consumption for irrigating crops
	Seed or seedling	Cost of seed and seedling for planting crops or trees
	Food production	Provision of crops, fruits, vegetables, poultry, livestock, aquatic products, and foraging
Goods and services (Output)	Basic livelihood security	Providing the minimum necessities for a sustainable life for a farmer
	Employment	Stable employment opportunities provided by agriculture
	Aesthetic and recreation	Aesthetics, spiritual and psychological care, sense of place, leisure and ecological tourism, agricultural education services, etc.
	Carbon sequestration and oxygen release	Maintaining the balance of the atmospheric chemical composition by absorbing CO <sub>2</sub> and releasing O <sub>2</sub>
	Soil and water conservation	Effect of vegetation on soil retention and reduction in soil erosion
	Air purification	Ecological landscape absorption of SO <sub>2</sub> , NO <sub>x</sub> , dust, etc.
	Climate regulation	Regulating regional climate, such as increasing precipitation and decreasing the temperature
	Water purification and waste treatment	Decomposition and removal of residua and excess nutrients, purification of water
	Biodiversity	Maintaining the diversity of biological species
	Raw material production	Wood, forest products, medicinal plants, spices, etc.
	Hydrological regulation	Flood control and water storage
	Pest control and pollination	Pest and disease control, habitat for pollinators

basic livelihood security, tourism and leisure services, carbon sequestration, oxygen release, air purification, water conservation, climate regulation, and biodiversity conservation. We also employed ecosystem service evaluation models to evaluate the services or functions of agricultural outputs and create spatial layers. According to a survey of inputs to agricultural production in the XMZ, our study also selected seven cost items: fertilizer, pesticides, plastic film, power of agricultural machinery, labor, seed and seedling costs, and water. By calculating the total value of the input and output indicators, we can measure and analyze land use efficiency and the spatial-temporal characteristics of urban agriculture.

### 3.3 Assessment methods

#### 3.3.1 Input models

##### (1) Agricultural input

Agricultural inputs, including chemical fertilizers, agricultural plastic film, pesticide, and power for agricultural machinery, were measured using the quantity used for agricultural activity per unit area and price. Then, we gridded data from the county to pixel scale and produced grid layers of inputs according to the spatial distribution of different types of agri-

cultural land. Here, the land use types were arable land, orchard, woodland, grassland, water body, and others. For instance, the measurement formulation for chemical fertilizer is as follows.

$$G_{ij} = \frac{G_i}{S_{ij}} \times b_{ij} \times m \quad (1)$$

where  $G_{ij}$  represents the total value of fertilizer application of the  $j$ -th land type in the  $i$ -th district or county;  $G_i$  represents the total quantity of fertilizer applied in the  $i$ -th district or county;  $b_{ij}$  is the fertilizer proportion of the  $j$ -th land type in the  $i$ -th district or county;  $S_{ij}$  is the total area of the  $j$ -th land type in the  $i$ -th fertilizer; and  $m$  is the chemical fertilizer price.

In this study, in order to describe the actual cost of agricultural land use and compare the changes between different years, including outputs described as follows, all prices related to costs and outputs were deduced according to the price increase factors.

### (2) Seed or seedling cost

We used the amount of seed or seedling per unit area invested in cropland or forest, multiplied by the price of seed or seedling, to evaluate its cost and then created grid layers according to the distribution of farmland or forest:

$$M_j = x_j \times q_j \quad (2)$$

where  $M_j$  represents the cost of seed or seedling in the  $j$ -th land type per unit area;  $x_j$  represents the average quantity of seed or seedling input per unit area of the  $j$ -th land type; and  $q_j$  represents the price of the seed or seedling.

The costs of water consumption by agricultural activities were evaluated similarly.

### (3) Labor cost

Labor costs were evaluated using the number of people in each agricultural sector and per capita agricultural income of farmers and gridded using the land use map:

$$N_j = a_j \times c_i \quad (3)$$

where  $N_j$  is the labor cost per unit area of the  $j$ -th agricultural sector (or land use type);  $a_i$  is the number of laborers input per unit area of the  $j$ -th agricultural sector; and  $c_i$  is the per capita agricultural income of a farmer in the  $i$ -th county.

## 3.3.2 Output models

### (1) Economic production

Economic production is the major agricultural output, and primarily represents the provisioning services from the agro-ecosystem, including food and raw material production from farming, fruit production, forestry, animal husbandry, and fisheries. Therefore, these values were assessed using the total output value from the listed provisioning services. These economic statistical data were gridded from the county to pixel scale, and the raster layers were generated from the land use map; the provisions are closely related to the arable land, orchard, woodland, grassland, and fishing water areas. The calculation of economic production was based on the production of wheat, corn, fruits, and fish with a price normalization factor to exclude the impact of price changes:

$$V_{ij} = \frac{v_{ij}}{s_{ij}} \quad (4)$$

where  $V_{ij}$  represents the value of the provisioning services per unit area of the  $j$ -th land use



type in the  $i$ -th county or district;  $v_{ij}$  represents the total output value from the  $j$ -th agricultural land type in the  $i$ -th district; and  $S_{ij}$  represents the total area of the  $j$ -th agricultural land type in the  $i$ -th district.

## (2) Basic livelihood security function

Basic living security function refers to the agricultural production activities that provide sustainable living for rural inhabitants. These residents have a minimum livelihood security that is not provided by government; therefore, this function refers to the lowest stable income that maintains their basic livelihood. This cost gain from agricultural operation may account for a large proportion of the total agricultural output value in a rural area. Therefore, in this study, we evaluated the economic value of basic livelihood security function using the total output value of agriculture and average proportion of the basic livelihood cost (0.36435) (Wang 2004, 2005). These values were gridded to a raster layer using the land use map:

$$K_{ij} = V_{ij} \times w \quad (5)$$

where  $K_{ij}$  represents the value of basic livelihood security function of the  $j$ -th agricultural land type in the  $i$ -th district;  $V_{ij}$  represents the total output value of the  $j$ -th agricultural land type in the  $i$ -th district; and  $w$  represents the average proportion of the basic livelihood cost to the total agricultural output value.

## (3) Aesthetic and recreation

The values of aesthetic and recreation were evaluated using the potential value of agricultural tourism and leisure per unit area from different agricultural landscapes and activities, and then normalized to the population density:

$$Q_{ij} = v_i \times p_i \quad (6)$$

where  $Q_{ij}$  represents the aesthetic and recreation service value of the  $j$ -th agricultural land type in the  $i$ -th district;  $p_i$  represents the ratio of the  $i$ -th district population density to the average population density of the year; and  $v_j$  represents the tourism and leisure function value of the  $j$ -th agricultural landscape or activity per unit area (Table 2).

**Table 2** Aesthetic and recreation value per unit area for each type of agricultural landscape in the Xi'an metropolitan zone ( $10^4$  yuan·ha<sup>-1</sup>·a<sup>-1</sup>)

Land use	Arable land	Woodland	Grassland	Water body	Orchard
1999	0.00082	0.10480	0.00328	0.35533	0.05404
2006	0.00142	0.18099	0.00565	0.58299	0.09333
2015	0.00252	0.32276	0.01009	1.09436	0.16642

## (4) Carbon sequestration and oxygen release

The value of air regulating services was evaluated using the photosynthesis equation (Zhou *et al.*, 2013; Fan *et al.*, 2013):

$$V_{ci} = 1.63 \times B_i \times R_c \times P_c \quad (7)$$

where  $V_{ci}$  represents the value of carbon sequestration per unit area of the  $i$ -th agricultural land type;  $R_c$  represents the carbon content of CO<sub>2</sub> (27.27%);  $B_i$  represents the net primary productivity (NPP) in the  $i$ -th agricultural land type (Table 3); and  $P_c$  represents the price of solid carbon (260.9 yuan/t).

$$V_{oi} = 1.19 \times B_i \times P_{o2} \quad (8)$$

where  $V_{oi}$  represents the value of oxygen release per unit area in the  $i$ -th agricultural land

type;  $P_{O_2}$  represents the oxygen price (376.47 yuan/t); and  $B_i$  is defined for Eq. (7).

**Table 3** NPP per unit area for each agricultural land use type in the Xi'an metropolitan zone ( $\text{t} \cdot \text{ha}^{-1} \cdot \text{a}^{-1}$ )

	Arable land	Woodland	Grassland	Water body	Orchard
1999	3.6235	7.3043	2.5339	2.0016	4.0168
2006	3.5277	7.2066	2.5082	1.9799	3.8176
2013	3.0757	6.8075	2.4594	1.8765	3.0065

### (5) Air purification

Air purification includes vegetation that retains dust, sterilizes the air, and absorbs harmful gases. In this study, we evaluated the economic values of absorbing  $\text{SO}_2$ ,  $\text{NO}_x$  and HF, and retaining dust in agricultural landscapes:

$$W_{ij} = A_{ij} \times P_{ij} \quad (9)$$

where  $W_{ij}$  represents the value of absorbing the  $j$ -th type of pollutants per unit area by the  $i$ -th agricultural landscape;  $A_{ij}$  represents the amount of the  $j$ -th type of pollutants absorbed per unit area (Table 4); and  $P_{ij}$  represents the treatment cost of the  $j$ -th type of pollutants per unit weight ( $\text{SO}_2$ : 0.6 yuan/kg; HF: 0.9 yuan/kg;  $\text{NO}_x$ : 0.63 yuan/kg; dust: 0.17 yuan/kg) (Yu *et al.*, 2005; Han and Zhou, 2015).

**Table 4** Pollutants absorbed per unit area for each agricultural landscape in the Xi'an metropolitan zone ( $\text{kg} \cdot \text{ha}^{-1} \cdot \text{a}^{-1}$ )

Land use	Pollutant types			
	$\text{SO}_2$	$\text{NO}_x$	HF	Dust
Woodland	291.03	215.36	9.94	44300.00
Grassland	21.70	16.06	1.20	120.00
Arable land	45.00	33.30	0.33	940.00
Orchard	90.00	66.60	0.79	9000.00
Water body	427.15	316.17	3.56	8.86

### (6) Water conservation

The water conservation service that is provided by arable land was calculated using the water storage capacity in soil:

$$V_1 = W \times C \quad (10)$$

$$W = \rho \times h \times p \times s \quad (11)$$

where  $V_1$  represents the value of water conservation per unit arable land;  $W$  represents the amount of water resource retained per unit arable land;  $C$  represents the average built cost per  $\text{m}^3$  of reservoir capacity in China (0.67 yuan/ $\text{m}^3$ );  $\rho$  represents soil bulk density ( $1.37 \text{ g/cm}^3$ );  $h$  represents soil thickness (0.2 m, tillage depth);  $p$  represents soil moisture content (22.3%), and  $s$  represents the area of arable land.

The water conservation service provided by woodlands, orchards, and grasslands was calculated using the method of comprehensive water storage capacity:

$$V_2 = (Q_1 + Q_2 + Q_3) \times C \quad (12)$$

$$Q_1 = r \times l \times s \quad (13)$$

$$Q_2 = f \times q \times s \quad (14)$$

$$Q_3 = h \times k \times s \quad (15)$$

where  $V_2$  represents the value of water conservation in woodlands, grasslands, and orchards;  $Q_1$ ,  $Q_2$ , and  $Q_3$  represent the ratio of canopy rainfall interception, water holding capacity of the litter layer, and precipitation reserves in soil, respectively;  $r$  represents precipitation;  $l$  represents the interception ratio by canopy;  $s$  represents the area of woodlands, grasslands, and orchards;  $f$  represents the dry weight of the litter layer;  $q$  represents the saturated water absorption ratio;  $k$  represents the soil non-capillary porosity (Table 5); and  $C$  and  $h$  are defined as in Eqs. (10) and (11).

**Table 5** Water conservation parameters for each agricultural landscape in the Xi'an metropolitan zone (Liu *et al.*, 2016)

	Dry weight of litter layer (t/ha)	Saturation absorption rate (%)	Canopy interception rate (%)	Non-capillary porosity (%)
Woodland	24.56	276.45	19.35	13.46
Orchard	9.27	155.00	6.56	6.34
Grassland	4.43	40.74	4.10	6.07

### (7) Climate regulation and biodiversity conservation services

The evaluation of climate regulation and biodiversity conservation services was conducted using the equivalent factors for ecosystem service value in the XMZ (Zhou and Qiu, 2011; Hu and Zhou, 2013), which were modified from a similar table for China (Xie *et al.*, 2008, 2015) according to the region's characteristics (Table 6).

**Table 6** Climate regulation and biodiversity value per unit area for each agricultural land use type in the Xi'an metropolitan zone ( $10^4$  yuan·ha<sup>-1</sup>·a<sup>-1</sup>)

	Arable land	Woodland	Grassland	Water body	Orchard
Climate regulation	0.135	0.409	0.136	0.350	0.273
Biodiversity	0.108	0.591	0.295	0.002	0.442

### 3.3.3 Comprehensive efficiency of agricultural land use

The comprehensive efficiency of agricultural land use was calculated using the cost-benefit model:

$$E = O - I \quad (16)$$

where  $E$  is the comprehensive efficiency of agricultural land use;  $O$  is the sum of the value of the nine output indicators of agricultural land; and  $I$  is the sum of the value of the seven input indicators for agricultural land.

## 4 Results

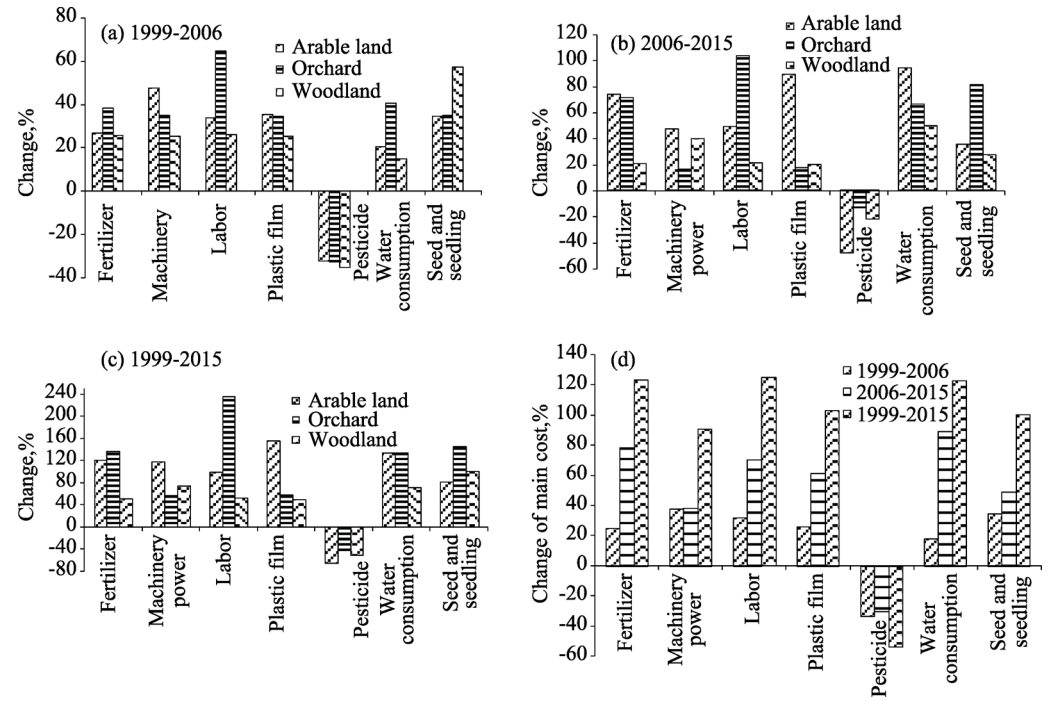
### 4.1 Change in input

With the rapid economic development and urbanization in the XMZ, agriculture is transforming from traditional cereal to urban modern cultivation. The region has witnessed large-scale development of orchards, leisure and sightseeing agriculture, and other commercial agriculture in the last 20 years. Concurrently, the cost of agricultural production has dramatically increased. (Tables 7–9 and Figure 3). Due to the common price increase of agricultural labor, fertilizer, seeds and seedlings, agricultural plastic film, irrigative water re-

sources, and power for agricultural machinery, the cost inputs per hectare of agricultural land have been increasing since 1999 (Table 7). Although agricultural pesticide usage has rapidly declined by 64.9%, 49.8%, and 41.4% across arable land, orchards, and woodlands, respectively, the costs for other agricultural input materials consistently increased from 1999 to 2015. Labor and fertilizer costs had the largest increase, respectively averaging 124.9% and 123.1% per hectare. The costs of seeds and seedlings, water consumption, and plastic film all increased over 100%, and the cost of machinery power rose more than 90%. In the agricultural sectors, the total input costs for orchards and arable land went up 15,600 yuan and 9900 yuan, or 151% and 103.5% per hectare, respectively. In comparison, forest costs merely increased by 38.2% from 1999 to 2015. The large-scale development of fruit production in the XMZ drove up the costs for orchards: labor, fertilizer, water consumption, and seed and seedling costs rose by 235%, 133%, and 145%, respectively. The increases in costs for crop production were mainly driven by plastic film usage, water consumption, fertilizer, and machinery power, which respectively rose by 156.6%, 133.9%, 120.8% and 117.5%.

**Table 7** Change in input per unit area for each agricultural land type in the Xi'an metropolitan zone

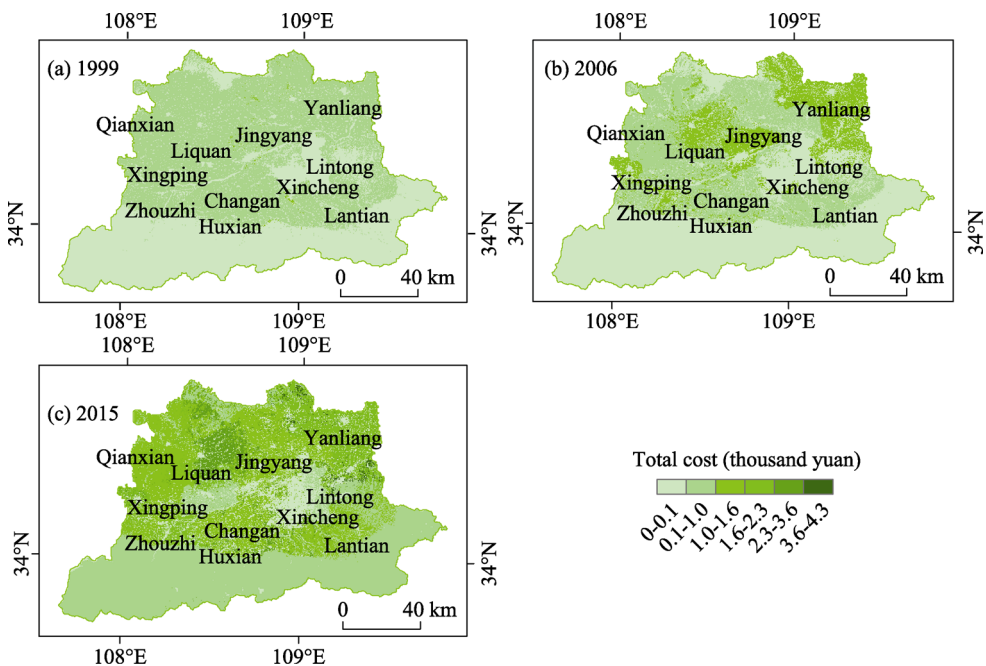
	1999–2006		2006–2015		1999–2015	
	Amount of growth(yuan/ha)	Change (%)	Amount of growth (yuan/ha)	Change (%)	Amount of growth (yuan/ha)	Change (%)
Arable land	2198.81	0.28	5788.78	58.37	7987.589	103.49
Orchard	4405.87	0.43	11274.00	76.35	15679.867	151.35
Woodland	108.28	0.13	211.89	22.39	320.170	38.19



**Figure 3** Change in main agricultural costs per unit area for agricultural land

There were significant spatial variations in agricultural costs over the XMZ between 1999, 2006, and 2015 due to the differences in urbanization and agricultural transformation

(Figure 4). Due to the conversions of land use and agricultural transformations from rapid urbanization, per unit area cost changes showed significant growth, and areas of high cost value increased from 1999 to 2015. The lowest agricultural inputs were in southern Qinling Mountains and the northwestern loess tableland of Liquan and Qianxian counties, which primarily comprise woodland, have fewer cultivated areas, and have lower proportions of reclaimed land. In contrast, the high cost areas mostly encompass the urbanized area of Xi'an and Xianyang cities, and were distributed in the northeastern and western parts with large areas of high-quality arable land, such as Yanliang, Jingyang and Wugong, Yangling counties. In general, the spatial changes in agricultural input were dominated by the expansion of orchards, primarily apple, grape, kiwi, and pomegranate orchards, and the transformation from cereal production to fruit production, recreation agriculture, and nursery forest activities. First, the agricultural transformation was driven by urbanization in suburban areas from cereal production to vegetable, fruit, nursery and flower production, and leisure agriculture. Subsequently, regional economic improvement, construction of a modern urban agricultural base, and agricultural intensification drove the expansion of the high added value urban agricultural sector to the broader areas far from the cities. Therefore, the demand for agricultural products promotes the conversion and diversification of agricultural land use in the process of rapid urbanization through the development of tourism agriculture, flower production, nurseries, and orchards. These processes promote the evolving spatial pattern of agricultural cost in the XMZ. Generally, the inputs to agricultural production were closely related to economic development and type of agricultural land.



**Figure 4** Spatial changes in agricultural land inputs in the Xi'an metropolitan zone from 1999 to 2015

### 4.2 Change in output

The total output value gradually grew in the XMZ from  $3.97 \times 10^{10}$  yuan in 1999 to  $5.60 \times 10^{10}$  yuan in 2015, an increase of 41%. The combination of different agricultural sector charac-

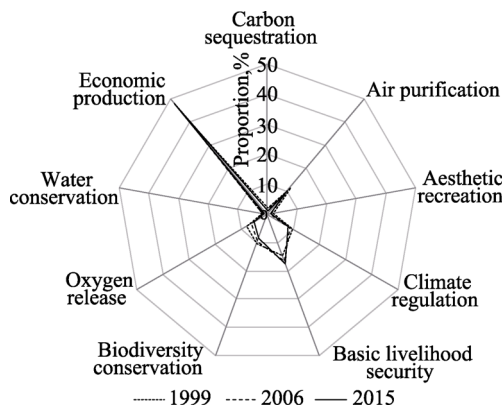
teristics and disparate intensification of agriculture over the study area highlights the variable land utilization. During the past 15 years, the total output from arable land increased the most, 80.2%, compared to the 14.9%, 14.0% and 10.6% increases from livestock, fishery, and fruit products in grassland, water body, and orchards (Table 8). In addition, the diverse agro-ecosystem services and functions (namely outputs) changed significantly as a result of agricultural transformation and large-scale landscape patterns from 1999 to 2015. The economic production function and basic livelihood security function each rose by 70%, the climate regulation, biodiversity conservation, and air purification services increased more than 11%, while aesthetic recreation, carbon sequestration, and oxygen release services dropped by over 9.8%. The increases in total output value were dominated by the economic production function from the urban agro-ecosystem, which accounted for 40%, 45%, and 48% in 1999, 2006, and 2015 respectively. Furthermore, the spatial distribution indicated that the entire study area had an increase in total output from 1999 to 2015 (Figures 5 and 6). The high value areas were evenly distributed across arable land area in the middle and northern plain in 1999. These expanded to the outer-fringe areas of the central urbanized area and the newly planted orchards in 2006, and continued to expand far from the urban area in 2015. The lower value areas were still distributed in the southern forest area of the Qinling Mountains. These results indicate that the economic output from agricultural land has one of the most important roles in urbanized areas, where human activities affect the agro-ecosystem to a greater degree. In remote areas, there were more transformations from large-scale cereal production because they can provide more supporting and regulating services and relatively lower provisioning services. The city's industrialization and market demand for agricultural production, such as vegetables and fresh fruits, and for leisure, drive the transformation in suburban areas from cereal production to orchards, vegetable plantations, and leisure agriculture park; these activities provide higher economic output at earlier stages of urbanization, and then they expand to the rural areas far from the central city. Therefore, urban agricultural development and the high production in orchards, such as kiwis in Zhouzhi, grapes in Huxian, and pomegranates in Lintong, have increased agricultural economic outputs, and increased labor wages and quality of life. In addition, the value of tourism and leisure services has increased significantly due to the demand for recreational water bodies and woodland landscapes, which has also improved the ecosystem efficiency.

**Table 8** Change in output per unit area for each type of agricultural land in the Xi'an metropolitan zone

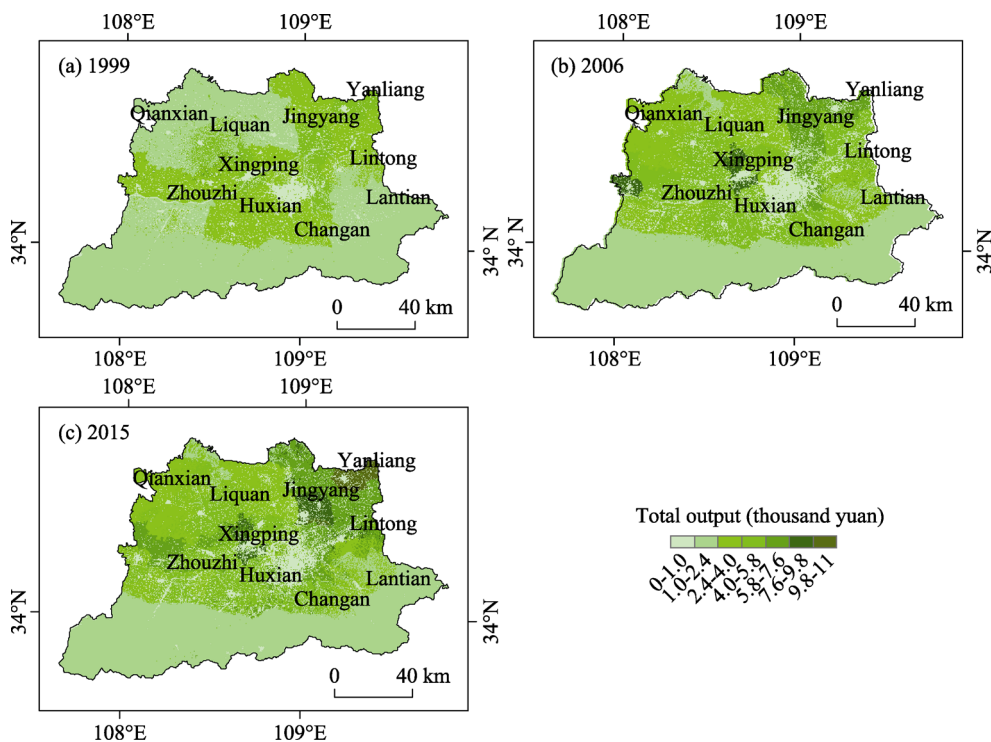
	1999–2006		2006–2015		1999–2015	
	Amount of change (10 <sup>4</sup> yuan/ha)	Rate of change (%)	Amount of change (10 <sup>4</sup> yuan/ha)	Rate of change (%)	Amount of change (10 <sup>4</sup> yuan/ha)	Rate of change (%)
Arable land	1.70	55.66	0.75	15.77	2.45	80.21
Orchard	−0.46	−8.03	1.06	20.24	0.60	10.59
Woodland	0.17	7.10	−0.09	−3.43	0.08	3.42
Grassland	0.45	53.55	−0.32	−25.16	0.12	14.19
Water body	−0.06	−3.85	0.29	18.61	0.23	14.04

**4.3 Change in comprehensive land use efficiency**

The value of agricultural land use efficiency per hectare increased on average from  $2.38 \times 10^4$  yuan



**Figure 5** Primary changes in agricultural land use outputs in the Xi'an metropolitan zone from 1999 to 2015



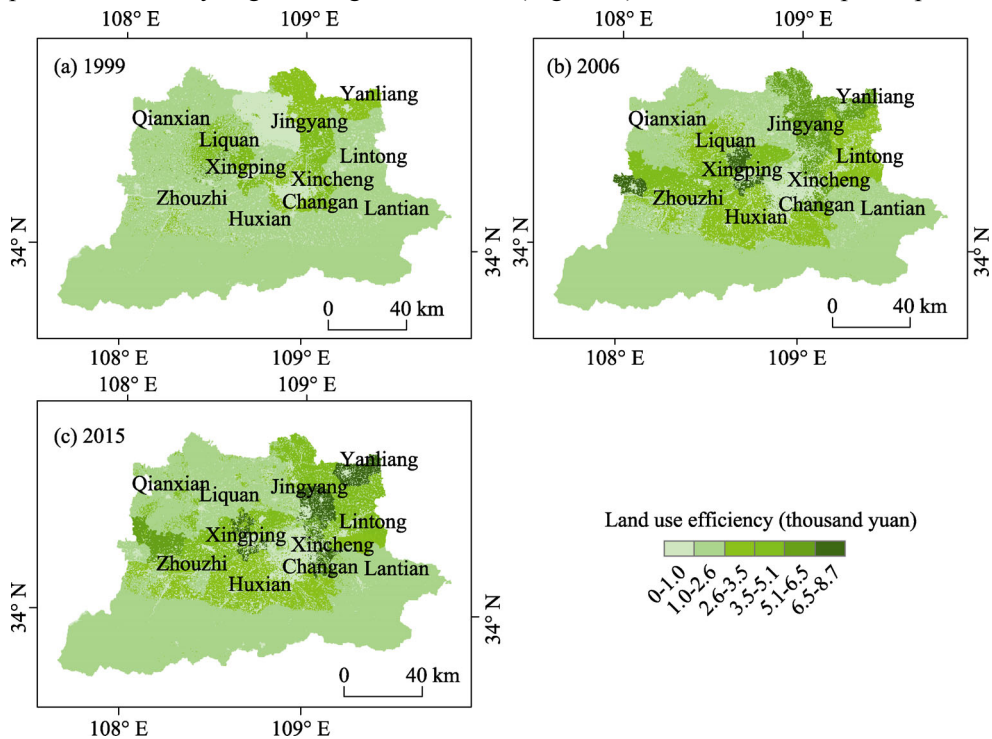
**Figure 6** Spatial changes in agricultural land output in the Xi'an metropolitan zone from 1999 to 2015

to  $3.17 \times 10^4$  yuan, a 33.13% increase, from 1999 to 2015. However, the rate of change significantly varied for different agricultural sectors. The efficiency of arable land increased by 70% primarily because of the transformation from cereal production to high-value urban agricultural activities, such as the cultivation of vegetables, strawberries, or melons, which give higher profits than cereal or rapeseed production, and agricultural intensification. The efficiency of fisheries went up by 14% due to production growth and the expansion of the area for aquatic cultivation. Forestry efficiency also increased due to the change from deforestation to afforestation. In contrast, fruit production efficiency dropped 20%; the benefits declined in comparison to the dramatic increase in costs associated with the small growth in outputs of fresh fruit production and insufficient processing of agricultural products (Table 9).

**Table 9** Change in agricultural land use efficiency per hectare for each land type in the Xi'an metropolitan zone

	1999–2006		2006–2015		1999–2015	
	Amount of change (10 <sup>4</sup> yuan/ha)	Rate of change (%)	Amount of change (10 <sup>4</sup> yuan/ha)	Rate of change (%)	Amount of change (10 <sup>4</sup> yuan/ha)	Rate of change (%)
Arable land	1.48	39.33	0.17	4.56	1.65	72.36
Orchard	−0.90	−23.90	−0.07	−1.83	−0.97	−20.77
Woodland	0.16	6.44	−0.11	−4.42	0.05	2.16
Water body	−0.06	−4.01	0.29	18.61	0.23	14.04

In general, the land use efficiency of agriculture clearly increased in most parts of the XMZ from 1999 to 2015. The higher efficiency areas were primarily for vegetable and melon cultivation, forest nurseries, and some orchards as a result of the early agricultural transformation in the process of urbanization and agricultural development. The areas near the regional central cities and scattered towns and main traffic roads had high values. For instance, Yanliang, Jingyang, Xingping, Liquan, and Yangling first had crop land altered to orchard or vegetable land and leisure agricultural land because these products can be transported to urban market conveniently and sold for high prices, or there were large numbers of tourists that provided high profits. However, areas far from cities, towns, and main roads, such as Qianxian and Lantian, maintained large areas of cereal production and had lower efficiency values. In addition, the southern part of the Qinling Mountains, primarily covered by forest, was a low-value zone because of the required high inputs for forestation and production of few forest products with lower economic production value; however, these areas do provide relatively high ecological services (Figure 7). Therefore, the spatial pattern of



**Figure 7** Spatial changes in agricultural land use efficiency in the Xi'an metropolitan zone from 1999 to 2015



changing agricultural land use efficiency was to a great extent determined by the transport of agricultural products, namely by the degree of urbanization and agricultural transformation to urban agriculture.

## 5 Discussion and conclusions

### 5.1 Discussion

At present, the economic outputs from agricultural land are recognized as the sole output by officials, farmers, scholars, and society at large, and the social and ecological outputs are being ignored. This discrepancy provides an incomplete understanding of agricultural multi-functionality and an underestimation of the actual outputs from agricultural land. Furthermore, this can lead to poorly organized agricultural planning and poor land use policy-making. Essentially, urban agro-ecosystems provide critical provisions and ecological support services for cities, far beyond their economic production (Wang and Zhou, 2014). In this study, from the perspective of agricultural multi-functionality, we developed a comprehensive evaluation framework for urban agricultural land use efficiency. In particular, the social and ecological services and functions provided by dry farming in the Guanzhong Plain were included as outputs from agricultural land. By employing this new ecosystem service assessment model to calculate agro-ecosystem service or function and the costs at a pixel scale, we measured the comprehensive efficiency of agricultural land use, and analyzed the spatial-temporal changes in urban agricultural land use efficiency in a rapidly urbanized and cultivated area. These improvements could mitigate the deficiencies in traditional research. We took the mean proportions of the economic efficiency from the traditional evaluation result and compared them to the comprehensive efficiency results from the method proposed here. We calculated the correlation coefficient between them using data from 600 random sampling points within the study area, and examined the differences between the two methods (Table 10). The results demonstrate that the economic output accounted for 40%, 45%, and 48% of the total output from agricultural land in 1999, 2006, and 2015, respectively. The comprehensive outputs provided by this method are 2.1 to 2.4 times the economic outputs assessed using traditional methods, which is in agreement with other findings (Costanza *et al.*, 1998). Furthermore, the economic efficiency from land use accounts for 40%, 51.8% and 47.7% of the comprehensive efficiency per pixel of arable land for 1999, 2006, and 2015, respectively. These results indicate that the land use efficiency values calculated using this method are 1.93 to 2.48 times higher than the values calculated using the traditional method for arable land, and are 2.17 to 3.18 times higher than the values calculated using the traditional method for orchards. The difference is due to the higher values for regulating and supporting services provided by orchards than by arable land. Therefore, the traditional method seriously underestimates the efficiency of arable land, orchards, and forest land. However, the land use efficiency for forests has a negative value due to large-scale forest afforestation and reforestation, wherein the inputs outweigh the outputs. The patterns of land use efficiency calculated based on this new comprehensive evaluation are in general agreement with traditional methods; the correlation coefficients between the results from the two methods are 0.768, 0.933, and 0.958 for 1999, 2006, and 2016 respectively. In addition, the similarity indicates that in urbanized areas, which are significantly

cultivated landscapes dominated by economic outputs, the incorporation of social and ecological services and functions does not affect their spatial pattern. However, in other areas that are less influenced by urbanization, the two approaches may show differences due to the weight of factors other than economic outputs on the evaluation.

**Table 10** Comparison of results from comprehensive efficiency and traditional economic evaluations in the Xi'an metropolitan zone

Land type	1999		2006		2015	
	Mean proportion (standard deviation), %	Correlation coefficient	Mean proportion (standard deviation), %	Correlation coefficient	Mean proportion (standard deviation), %	Correlation coefficient
Arable land	40.03 (13.28)	0.998	51.83(9.75)	0.998	47.65(12.68)	0.998
Orchard	46.14 (10.61)	0.996	38.16(7.82)	0.991	31.44(14.17)	0.980
Woodland	−3.07 (0.42)	0.901	−2.08(2.39)	0.932	−2.67(3.41)	0.962
Agricultural land		0.768		0.933		0.958

This framework incorporates the ecological and social service values of water bodies, orchards, and woodlands into the output evaluation system. These services (especially ecological services) play an important role in maintaining the provisions from regional ecosystem services and the sustainable development of farming areas where the natural vegetation coverage rate is low, and in rapidly urbanized areas where the natural ecological landscape is disrupted.

Spatially, the results obtained from the two methods slightly vary across the urban areas. The areas undergoing rapid urbanization with developed modern urban agriculture have initially higher land use efficiencies using both methods. In the Qinling Mountains area, the level of ecological efficiency is high; however, the comprehensive efficiency is low due to the lower economic and social output values. These findings indicate that the transformation from traditional agriculture to modern intensive agriculture can improve agricultural land economic efficiency in urban areas. However, these changes will lead to a significant decrease in ecological services resulting from the gradual fragmentation of the native landscape and extensive crop production that increase the number of changes to the ecosystem structure and processes. Improvements in economic efficiency are at the expense of high-value inputs and serious loss of ecological services. Because economic and social services had higher output values, the spatial patterns of comprehensive land use efficiency were determined by economic output patterns. Agricultural land use efficiencies were generally underestimated using traditional methods, and this was particularly true in the forest area of the Qinling Mountains. Despite the low values for horticulture and low costs in forest areas, the natural forest can provide ecological services and functions, such as climate regulation, hydrological regulation, water conservation, and biodiversity protection. The results, as evaluated using this framework, can objectively reflect the actual value and contribution of different types of land use.

This study proposes a new evaluation framework for agricultural land use efficiency and advocates for the government to sufficiently consider the broad number of outputs from different land use activities for agricultural policy-making. While this study has incorporated additional inputs and outputs for evaluating land use change, the selected agro-ecosystem (or

land use) services do not yet include all factors. Due to difficulties in data acquisition, some positive services, such as providing a habitat and pollination, mainly conducted by laborers in orchards in the study area, have not been incorporated into the evaluation framework. In addition, these evaluation indicators are mainly suitable to arid agriculture in temperate semi-humid areas. As an open evaluation framework for land use efficiency, if applied to other agricultural types or regions, these indicators should be modified to suit the corresponding agro-ecosystem and agricultural activities. Recently, some scholars have shown that an ecosystem can provide both beneficial and detrimental services or goods (Lyytimäki, 2014; Li and Zhou, 2016). However, the concept and understanding of an agro-ecosystem disservice is not yet clear. For instance, details of what an agro-ecosystem disservice includes, how they are formed, how to conduct a value evaluation, and whether disservices belong to the output or input items of agriculture have not yet been resolved. Therefore, agro-ecosystem disservices or detrimental factors, such as pollen allergies, are not considered in this study (Ma *et al.*, 2015). In addition, due to the limitations of the current assessment method for ecological services, such as for aesthetics and recreation services, the value was indirectly measured using equivalent factors for the ecological service value of terrestrial ecosystems in Xi'an; these values are not identical to values based on the willingness to pay, which tend to be more costly. The spatialization methods for statistical and survey data used for economic outputs and inputs also need further improvement. As such, further exploration and improvement in terms of scientific and practical feasibility are required.

The results show that agricultural land has great value in land use efficiency, which remains unrecognized by the government and agricultural producers, and requires attention. The lack of recognition leads to an unfair evaluation of the agricultural sector, which is not conducive to formulating policies related to agricultural subsidies and agricultural transformation. Existing agricultural policies in China mainly include subsidies for agricultural production, natural disaster relief, agricultural resource reserves, and agricultural environmental protection, but there are no subsidies for the provisioning value of agro-ecosystem services. In addition, agricultural producers do not have a full understanding of their land value; coupled with the relative decline in the price of agricultural products in comparison with the rapid increase of industrial production prices, these lead to poor farmer morale. Therefore, it is necessary to formulate a set of economic compensation policies to support the social and ecological service functions of agricultural land. This is especially urgent in suburban agricultural areas, where agricultural activities play an important role in the urban eco-environment. As such, urban agriculture should be given ecological payment, which also would encourage farmers to transform agricultural structures, shifting to greenhouse vegetable planting and fruit and high-yield crop cultivation, and stimulate enthusiasm for farming, increase farmer income, and protect the farmland eco-system.

As a whole, integrating social and ecological services from agricultural land as a portion of its output to the efficiency evaluation is important for understanding and evaluating agricultural land use efficiency. The evaluation framework in this study provides a mechanism for a more comprehensive decision-making process for ecosystem services and incentives for introducing agricultural production subsidies, agricultural transformation, and other policies. As a first step toward better policy-making, this study should be used to develop a more scientific approach for further research on agricultural land use efficiency. However, due to the current lack of theory and methods of agricultural multi-functionality research,

ecosystem services research is not well developed at this time, and the limitations described previously need to be addressed.

## 5.2 Conclusions

(1) With rapid urbanization and agricultural transformation from traditional cereal cultivation to modern urban agriculture, the costs, outputs of agricultural production, and land use efficiencies have been dramatically increasing. The total output value increased by 41% and agricultural land use efficiency per hectare averagely rose by 33.13% from 1999 to 2015 in the Xi'an metropolitan zone.

(2) The economic output from agricultural land is significant in urbanized areas, accounting for more than 40% of total output, and dominating the spatial pattern of total output and land use efficiency. The areas near cities, and distributed as orchard and arable land, have provided more economic function and supporting and regulating services due to the transformation from extensive cereal production to intensive modern urban agriculture, such as orchard, forest nursery, and leisure agriculture. Therefore, these areas have increased their output and land use efficiency. However, the areas far from cities, towns, and main traffic roads, namely, remote rural areas, provide more supporting and regulating services, have relatively lower economic function and services, and have lower output and land use efficiency resulting from lower economic output. This contrast indicates that the spatial changes in output and land use efficiency of agriculture in urbanized areas are strongly determined by the degree of urbanization and agricultural transformation.

(3) This evaluation approach integrates economic, social, and ecological outputs from land use into a comprehensive output and employs newly developed fine spatial resolution methods for ecosystem services research. This approach is more accurate and methodical for evaluating comprehensive land use efficiency due to the small spatial scale (pixel scale) for valuation. The results demonstrate that the comprehensive output from agricultural land is 2.1 to 2.4 times as much as the economic output. Furthermore, the comprehensive land use efficiency valued using this approach is 1.93 to 3.18 times higher than the economic efficiency assessed using the traditional method for arable land and orchards. These findings also indicate that in urbanized areas with more intensive urban agriculture, the spatial pattern measured using this evaluation framework provides similar results to those from a purely economic evaluation; the spatial pattern of comprehensive land use efficiency is largely determined by the pattern of economic output.

(4) The total output value and land use efficiency of urban agriculture measured using this framework are much higher than those found from traditional evaluation methods. These evaluations have important implications for enhancing current agricultural subsidies and even implementing an ecological payment policy in China. Further, the approach provides a mechanism for assessing the contrasts and changes between economic efficiency and ecological efficiency in the process of agricultural transformation. These evaluations can be directly applied to agricultural transformation, decision-making, and guidance for rational land utilization.

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