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System Cognition and Analytic Technology of Cultivated Land Quality from a Data Perspective

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Abstract: As cultivated land quality has been paid more and more scientific attention, its connotation generalization and cognitive bias are widespread, bringing many challenges to the investigation and evaluation of regional cultivated land quality and its data analysis and mining. Establishing a systematic and interdisciplinary cognitive approach to cultivated land quality is urgent and necessary. Therefore, we explored and developed a conceptual framework of the model for the cultivated land quality analysis from the data perspective, including cultivated land quality ontology, mapping, correlation, and decision models. We identified the primary content of cultivated land quality perceptions and four cognitive mechanisms. We built vital technologies, such as the collaborative perception of the quality of cultivated land, intelligent treatment, diagnostic evaluation, and simulation prediction. Applying this analysis framework, we sorted out the frequency of indicators that characterize the function of cultivated land according to the literature in recent years and have built the cognitive system of cultivated land quality in the black soil region of Northeast China. The system's central component was production capacity and it had three components: a foundation, a guarantee, and an effect. The black soil region cultivated land quality evaluation system has seven purposes involving 20–31 key indicators: production supply, threat control, farmland infrastructure regulation, cultivated land ecological maintenance, economics, social culture, and environmental protection. In various application contexts, the system had many critical supporting technologies. The results demonstrate that the framework has strong adaptability, efficiency, and scalability, which might offer a theoretical direction for further studies on the evaluation of the quality of cultivated land in the area. The analysis framework established in this study is helpful to deepen the understanding of cultivated land quality systems from the perspective of big data. Taking the big data of cultivated land quality as the driving force, combined with the technical methods of cultivated land quality analysis, the evaluation results of cultivated land quality under different scenarios and different objectives are optimized. In addition, the framework can serve the practice of farmland management and engineering improvement, adapt to the management needs of different objects and different scales, and achieve the combination of theory and practice.

Keywords: cultivated land quality; system cognition; data mining; investigation and evaluation; black soil region of northeast China

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1. Introduction

The importance of cultivated land quality in guaranteeing national food security and the productivity of cultivated lands has drawn attention from academics and government organizations worldwide. Cultivated land quality is typically seen as a comprehensive reflection of many different characteristics [1]. However, it is not a cognitive unity, leading to structural variances in the arrangement of the elements. In 2003, Chinese government departments developed the "Farmland Grading Regulation" with light and temperature production potential, utilization level, and land benefit as the core, and released the national comparable farmland quality evaluation results for the first time in 2009 [2]. Based on this methodology, Chinese government departments classified the quality of cultivated land resources in 2019, emphasizing the features of cultivated land's ecological environment and natural resource endowment [3]. Similar traits can also be seen in the global mainstream cultivated land quality rating system [4,5]. The evaluation of cultivated land productivity is the main objective of the British land productivity classification system and the Canadian land suitability grading system, which also emphasizes the limitations of cultivated land variables on agricultural production [6]. The EU's system for assessing the environmental impact of soil is problem-focused and compares risk levels from several soil challenges to quality [7]. Site conditions and soil health are combined for evaluation and grading in Germany's Muencheberg soil quality grading system [8]. According to the Cornell framework for assessing soil health in the United States, soil quality entails the integration and optimization of soil chemical, physical, and biological processes, and it proposes matching evaluation indices based on these three processes [9]. For special management requirements, these works carried out the organic combination and thorough evaluation of cultivated land quality variables from diverse dimensions. The results reflect the complexity and cognitive differences of cultivated land quality, which are related and have different emphases.

To better understand cultivated land quality, the academic community attempted to categorize it. Soil quality frequently replaces cultivable land quality internationally. In general, academics concur that sustainability of soil quality is the ultimate goal of soil use and that the idea of soil quality extends beyond soil productivity to include human–soil interactions [10,11]. In order to maintain biological productivity, preserve environmental quality, and advance plant and animal health, soil quality is defined by Doran and Parkin as "the ability of soils to function within ecosystems and land-use limits" [12,13]. Later, the two categories of soil quality were dynamic soil quality and inherent soil quality [9]. Zhao suggested that, from the perspective of the cultivated land system, cultivated land quality in China should take production capacity, economic and social value, and cultivated land health into consideration [14]. According to Yun, the production capacity, the production environment, the capacity for self-recovery, and the safety of agricultural products should be used to gauge the quality of cultivated land [15]. The ability of cultivated land to perform ecological functions, offer ecosystem services to preserve biological production and environmental quality, and improve animal and plant health [16] is what Bunemann et al. characterize as the quality of cultivated land. With the increased interest in the study of cultivated land function among academics in recent years, many researchers have investigated and developed the evaluation system of cultivated land quality based on the fundamental framework of element function [17–19], which deconstructs cultivated land function from the perspectives of soil, geography, ecology, resource environment, landscape culture, economic society, and management, and makes a comprehensive theoretical analysis of the quality of cultivated land. However, it also causes uncertainty in the connotation and extension of the quality of cultivated land, complexity in element structure, ambiguity in the objectives and outcomes of evaluations, and even a disconnect with actual emotions. Zhang argued that the primary purpose of cultivated land is production, and that the best strategy to advance the study of cultivated land quality and provide scientific direction for management practice is to evaluate cultivated land quality with productivity at its heart [20].

The improvement of technology is a significant factor in the generalization of the quality of cultivated land. The traditional "small data" evaluation of a few factors with field sampling as the primary method of acquisition is going to evolve towards the data processing direction of multi-source data fusion of "Space-Air-Ground" as a result of the rapid development of emerging detection technologies such as ground survey, in situ monitoring, aerospace remote sensing, economic and social big data, and high-throughput sequencing. According to studies, there are more than 100 common evaluation indices and an upward tendency. Some data on the quality of cultivated land have large-scale, diverse, and dynamic characteristics, which are consistent with big data [21,22]. In the context of climate change, Cravero et al. constructed a big data processing system [23]. For agriculture surveys, some researchers attempted to build a monitoring data system [24,25]. In agricultural soils, Hemageetha presented several data mining methods [26]. Yao created a distributed technology-based big data processing approach for cultivated land [27,28]. The technical approaches of cultivated land quality study are enriched in the areas of information collecting, optimal scale analysis, and building evaluation index systems by data association analysis, information mining, and spatiotemporal prediction based on machine learning and other technologies [29–31]. On the other hand, because of the cultivated land quality's ambiguous meaning, the fundamental connection between the object of the assessment and the aim of the evaluation, real-world application scenarios, etc., the features and appropriate technological methods of the data on the cultivated land quality are imperfect and out of sync. Big data technology is a significant new path for assessment research in the fields of ecology, geography, and other related disciplines [32–36]. A study framework for cultivated land quality analysis based on the perspective of data must therefore be established in order to fully realize the value of data.

From the data perspective, this paper will analyze the fundamental meaning and primary components of the quality of cultivated land. It will then build a system for cognitive analysis of big data related to the quality of cultivated land based on actual management requirements. The assessment framework and significant breakthrough direction of the study of the quality of the cultivated land in the black soil region of China were presented as examples, and they served as a methodological foundation for the scientific implementation of the protection and enhancement of the quality of the cultivated land.

2. Cognitive Framework of the Cultivated Land Quality System from the Data Perspective

2.1. Cognitive Conceptual Model of the Cultivated Land Quality System

The quality of cultivated land is a comprehensive reflection of the interaction of the climate, soil, topography, utilization, and other elements, and it may be used to determine the production level and long-term viability of cultivated land. From the standpoint of the data value conversion mechanism of "data-information-knowledge-service", we may systematically recognize the quality of farmed land. Data serve as the basis for all of them, while information is the phenomena, knowledge is the essential component, and service is the goal. By observing, presenting, analyzing, evaluating, forecasting, and weighting the cultivated land quality, we can gradually create the ontology model, mapping model, correlation model, and decision model of cultivated land quality in order to realize the value conversion of cultivated land quality data (Figure 1).

2.1.1. Ontology Model of Cultivated Land Quality

The cognitive foundation is the cultivated land quality ontology model. The space–air–ground three-dimensional collaborative data acquisition system is used by the full-factor model to collect data from multiple sources and extract useful information. The ontological model of cultivated land quality now exhibits the traits of multi-factor, incremental, and universality due to the advancement of perception tools and the theoretical research on cultivated land quality depth. It can be used to support varied demands, different subjects, and different situations, in addition to supporting the definition and extension of the quality of cultivated land.

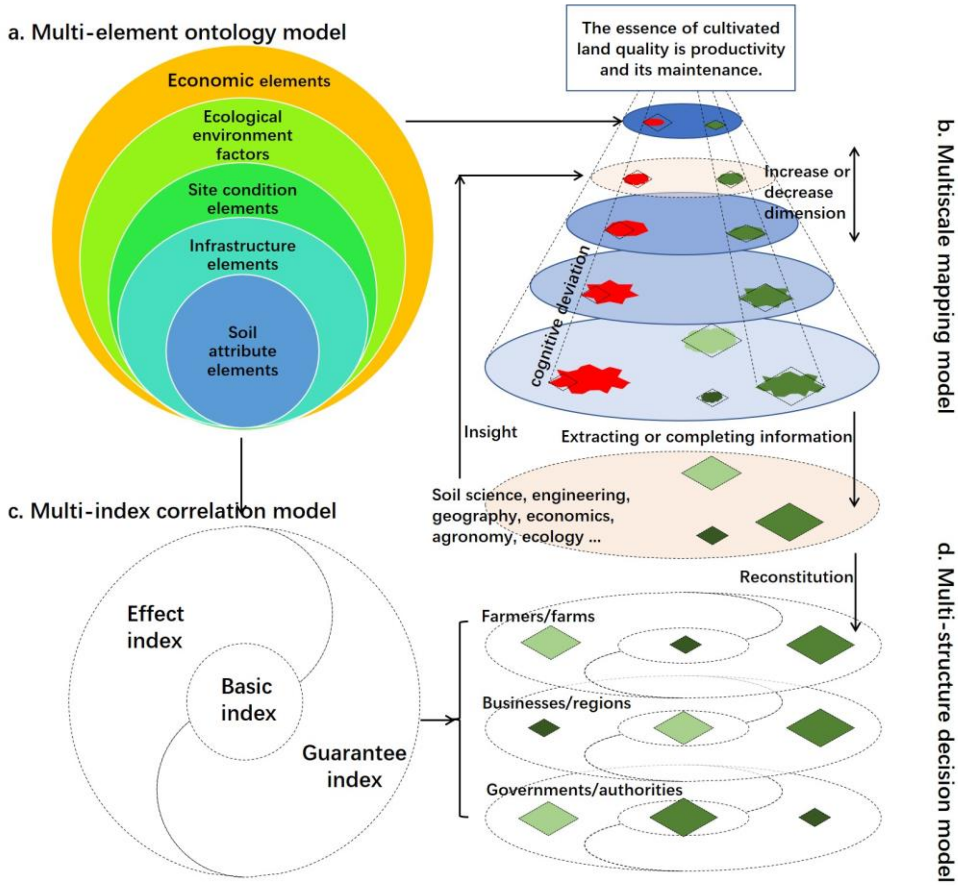

Figure 1. Cognitive conceptual model of cultivated land quality based on the data perspective. (**a**) Circles of different colors represent the different components of the cultivated land. The bottom-up range is getting larger and larger. (**b**) Circles of different colors represent different scales. The smaller the circle, the larger the scale. The figures in the circle represent the elements of cultivated land. As the scale decreases, the elements of cultivated land from the perspective of different disciplines become clearer. (**c**) Basic index is the key of effect index and guarantee index. (**d**) Three circles represent different scenes, in which the order of graphic position represents the different roles of farmland elements in different scenes.

2.1.2. Mapping Model of Cultivated Land Quality

The theoretical foundation is a mapping model of the quality of cultivated land. It is an "insight" model of the quality of cultivated land based on knowledge from various academic fields, such as soil science, geography, engineering, agronomy, ecology, and economics. The ontology model's cultivated land elements are organized logically in the mapping model, which has the traits of incompleteness, abstraction, and a solid theoretical justification. The mapping model serves as the theoretical underpinning for understanding a number of phenomena, including the mechanism of cultivated land quality formation, spatial and temporal differences, and its evolution process. It is also a crucial tool for achieving scientific management and service of cultivated land quality. As the factors have varying effects on the quality of cultivated land at various time and spatial scales, it is important to select the best theory to design a mapping model in accordance with the evaluation goal in order to prevent cognitive biases such as incomplete indicators, too fine indicators, and scales that are not the right fit, as well as the divergence between cognitive results and intuitive perceptions of cultivated land quality.

2.1.3. Correlation Model of Cultivated Land Quality

The cultivated land quality association model is an analytical strategy that serves as the foundation for exploring the theoretical associations of elements and implementing the quantitative analysis of indicators. The procedure and the components of the quality of the farmed land are connected. Therefore, it is crucial to develop critical components by identifying the core of cultivated land quality in various settings. A multi-level analytical framework of "key indicators-impact indicators-effect indicators" with capacity as the core can be established by differentiating between the influencing elements that have an impact on the formation process of the quality of cultivated land and the systematic effects brought about by changes in vital components based on this. These analyses illustrate the cognitive law of cultivated land quality from its fundamentals to its seen manifestations.

2.1.4. Decision Model of Cultivated Land Quality

The decision model of cultivated land quality is a service project that serves as the foundation for many objects that assist decision-making through analysis, assessment, simulation, and prediction, as well as the suggestion of management strategies for enhancing cultivated land quality. It is highly scene-oriented, goal-oriented, and management-oriented. Due to the various management demands for the quality of cultivated land, the fundamental components of various objects will be combined with various structural features, leading to various analytical outcomes to aid managers in making scientific decisions.

2.2. Basic Content of Cultivated Land Quality Cognition

2.2.1. Element–Process–Function of Cultivated Land Quality

The quality of cultivated land is influenced by a variety of variables, making it challenging for any one component to have a significant impact. Cultivated land components evolve gradually when the cultivated land definition is broadened and cultivated land function is manifested. The following five areas essentially correspond to it: soil characteristics, production security, site characteristics, ecological environment, economy, and society. The association between various elements becomes more difficult as the number of elements rises. For instance, the climate, topography, parent materials, biology, and other factors all have an impact on the soil conditions that are crucial to crop growth at the same time. Economic and social activities also have an impact on the regional natural resource conditions, and farmer behavior has an impact on the main operation of the cultivated land system. In order to clarify the favorable and unfavorable features of cultivating land, it is important to start with the definition of cultivated land quality, study cultivated land elements and their process relations holistically and systematically, take into consideration the matching relationship between scale differences, element characteristics, and cultivated land functions, and quantitatively measure and assess the combination of elements, coupling process, and primary functions.

2.2.2. The Foundation-Guarantee-Effect of Cultivated Land Quality

Grain production is the primary use of land that has been cultivated. Site and soil conditions influence crop growth and form the foundation of cultivated land quality. It is important to create appropriate infrastructural conditions through the development of farmland or to enhance farming conditions through artificial transformation, such as soil improvement, in order to sustain and increase the production level of cultivated land. Effects are a result of changes in cultivated land quality, and include things such as grain production capacity, input level, and other economic and social effects. The basic conditions, guarantee conditions, and effects of cultivated land quality should be converted or replaced under certain conditions (Figure 2). For example, precise and three-dimensional irrigation can effectively improve the problem of excessive waterlogging or drought of soil water content in the root zone of crops, that is, improving the guarantee conditions can overcome the basic obstacles caused by soil texture. As another example, the scale and shape of cultivated land will affect the use of agricultural machinery. On the field scale, agricultural machinery reflects the effect, while on the regional management scale, the mechanization degree can be considered as a guarantee condition.

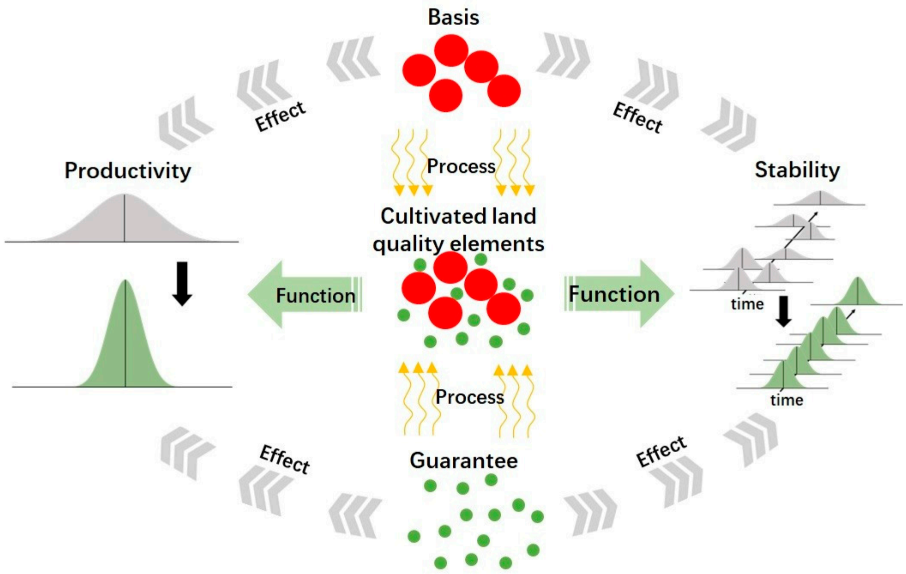

Figure 2. Factors of cultivated land quality and their correlation. The upper red circle represents the basic part of the cultivated land quality and the lower red circle represents the guarantee part of the cultivated land quality. The two are added together as the cultivated land quality elements. The function of cultivated land quality is reflected in productivity and stability. The left productivity graph is corresponding to the right stability graph, which means that the productivity of cultivated land is more and more concentrated and the stability is more and more strong with the change of time and the support of the foundation and guarantee part.

2.2.3. Formation Process and Stability of Cultivated Land Productivity

Cultivated land is a natural–artificial compound ecosystem. The generation of productivity and photosynthesis occur as a result of the coupling impact of several elements affecting the quality of the farmed land. Together, natural elements, such as light, temperature, water, and soil, as well as manmade factors, such as farming infrastructure, determine how productive the cultivated area is. Therefore, to maintain the stability of cultivated land productivity, it is necessary to ensure the synergy of many components through farmland infrastructure on the one hand, and to maintain system stability by manual intervention on the other. The former requires the necessary engineering work to develop a decent farming field and must be outfitted with an irrigation and drainage system, a road system, a power system, etc. The latter is responsible for ensuring the orderly development of the small cycle of crop growth and the large cycle of the ecosystem through the coordinated protection of the cultivated land and the surrounding grasslands and woods in the horizontal area, as well as the protection of the above-ground and subsurface biodiversity in the vertical direction, which is necessary in order to guarantee the cultivated land's capacity for self-purification, resilience, and dynamic stability of the cultivated land's quality throughout the production cycle. Consequently, farmland infrastructure and the biological environment of cultivated land are directly related to cultivated land production and should be included in the inquiry and evaluation of cultivated land quality as a crucial component of the definition of cultivated land.

2.2.4. Relationship between Cultivated Land Quality and Human Activities

Cultivated land is a semi-artificial ecosystem affected by human activities, which can be divided into direct and indirect impacts. The direct impact is mainly the impact of agricultural production activities, including agricultural input, production process interference, farmland construction, and management measures. The indirect impact is mainly the impact of non-production activities, such as changes in land use, development and construction activities, and agricultural structure adjustment. The quality of cultivated land will also affect human decision-making on land use. For example, a better quality cultivated land indicates that higher grain production capacity, farmers' income, and landscape cultural, affecting human behavior and management decisions. Therefore, the interaction between the quality of cultivated land and human activities reflects the evolution of the internal mechanism of the cultivated land system and the interoperability of the external environment of the economy and society. It is the theoretical basis for the service and value balance provided by cultivated land.

2.3. Cognitive Theory and Method of Cultivated Land Quality Big Data

2.3.1. Conversion Mechanism of "Data-Information-Knowledge-Service"

Data are the foundation, information manifests as a phenomenon, acquiring knowledge is essential, and service is the purpose of data processing. The primary mechanism of the value conversion of cultivated land quality data is:

(1) To obtain all-element arable land quality data;
(2) Processing the cultivated land quality data to refine adequate information;
(3) Applying evaluation methods such as optimization of soil spatial sampling points, zoning clustering, knowledge map construction, and prediction methods such as multi-scale farmland pattern characterization and farmland simulation model construction to acquire more knowledge of farmland quality;
(4) To provide support and a basis for management decisions such as cultivated land quality improvement and cultivated land protection.

2.3.2. Explanation Mechanism of "Phenomenon-Threat-Representation-Essence"

Through observation, monitoring, and assessment, we can learn about the phenomenon of changed cultivable land quality. Then, based on specialized knowledge and experience, we can assess the negative trend of changing cultivated land quality. Then, we can use machine learning, data mining, and other techniques to filter the main threat signs. Finally, we can comprehend the fundamental changes in cultivated land quality. Problems such as the deterioration of the quality of cultivated land can be controlled through all of these procedures.

2.3.3. Analysis Mechanism of "Scale-Spatial Pattern-Correlation-Evolution"

At various scales, the concept of the quality of cultivated land varies. By performing a geographical and temporal analysis on large-scale collected data on cultivated land quality, it is possible to determine the characteristics of the spatial distribution and pattern of cultivated land quality. The correlation and interaction of elements affecting the quality of cultivated land are then explored, and the process and mechanism of cultivated land quality evolution are next examined.

2.3.4. Decision Mechanism of "Scenario-Goal-Evaluation-Trade-off"

The scene is the main consideration for management. There are numerous application scenarios for cultivated land because it targets farmers, farms, businesses, regions, governments, and authorities. Various application scenarios usually have various objectives. For instance, whereas governments and jurisdictions place more emphasis on the usage of cultivated land resources and the stability and sustainability of production, farmers and farms tend to focus more on cutting production costs in order to maximize benefits. Therefore, in order to ensure the normal operation of cultivated land quality in various scenarios, it is necessary to weigh the objectives of cultivated land quality in various scenarios, choose various indicators to evaluate cultivated land quality according to different objectives, and then develop corresponding utilization and management strategies.

3. Technical Methods of Cultivated Land Quality Analysis Based on Big Data Cognition

The technology and method of cultivated land quality analysis were built from the aspects of collaborative perception, intelligent treatment, diagnostic evaluation, and simulation prediction of cultivated land quality, and the technical method of cultivated land quality analysis was expanded (Figure 3). This was performed in accordance with the cognition goal and demand of the cultivated land quality system, coupled with the big data processing method of cultivated land quality.

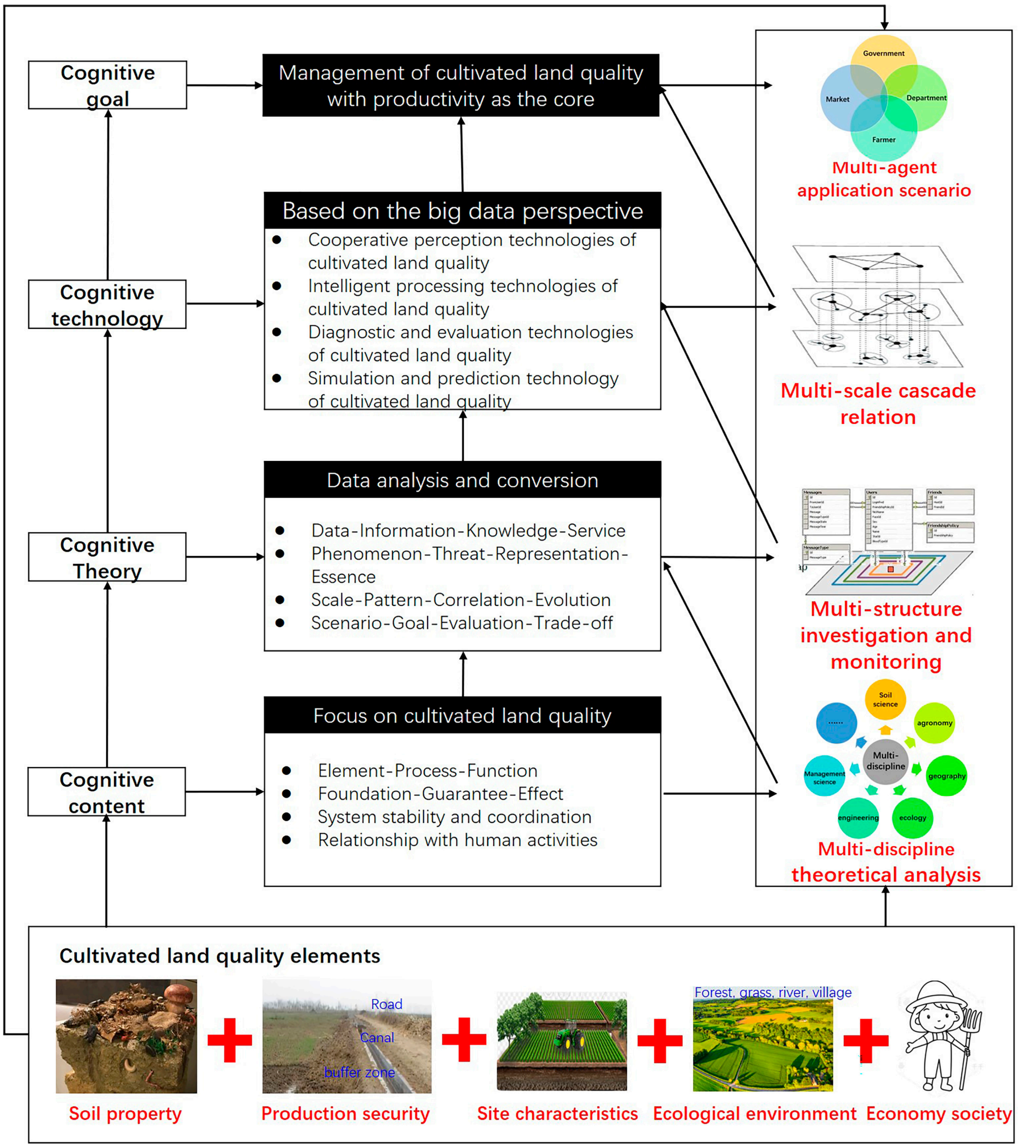

Figure 3. Technical System of Systematic Understanding and Analysis of Cultivated Land Quality. The picture below represents the different components of cultivated land quality. The content of cognitive content, cognitive theory, cognitive technology, and cognitive goal on the left corresponds to the middle block diagram, and the relationship corresponds to the picture on the right.

3.1. Cooperative Perception Technologies of Cultivated Land Quality

The elements that make up cultivated land quality are varied, complicated in their relationships, and different in their structures. Traditional ground survey techniques such as soil sampling detection and soil profile interpretation can fully describe the soil formation process and material migration and transformation laws of cultivated land through quantitative and qualitative analysis, and their distinctive advantages are difficult to replace; dynamic monitoring techniques based on remote sensing, ground sensors, stations, and other technologies can realize real-time, global, and three-dimensional perception, which can meet the requirements of large-scale, rapid and multi-dimensional information extraction, and high-precision parameter inversion, and avoid the accessibility and high-cost problems of conventional methods. Additionally, with the continual advancement of high-throughput sequencing, spectrum analysis, mass spectrometry, and other detection technologies in recent years, new indicators such as soil microorganisms [37–39], soil enzymes, microplastics [40], and trace elements in farmed land have reached reasonably quick and practical detection technology. Therefore, based on the core content of cultivated land quality cognition, we should take the extraction of element characteristics as the foundation, focusing on digging the association mode of cultivated land quality elements to the layer-by-layer deepening and information aggregation of the phenomenon, process, function, and effect analysis of cultivated land quality change, so as to strengthen the extended cognition of cultivated land quality from phenomenon to essence. The leading data analysis technologies here are:

(1) Space–air–ground integrated data collecting;
(2) Rapid ground survey and in situ monitoring;
(3) New cultivated land quality indicator identification.

3.2. Intelligent Processing Technologies of Cultivated Land Quality

Different sources of cultivated land quality factor data, inconsistent time and space standards, and unsatisfactory sample point positions will cause the data format to be difficult to unify, and the application scope of the analysis results will be limited [41]. These issues have become a "bottleneck" obstacle for the quantitative analysis of cultivated land quality. In order to regulate and efficiently handle complete elements, high-precision, and three-dimensional cultivated land quality and space data of ground and ground, the following technologies are required:

(1) Cultivated land quality multi-source data fusion technology, which addresses the issue of seamless fusion between various elements, various analysis units, and various time–space precision elements;
(2) Inadequate data integration and filling technology: the survey and monitoring data collected on isolated islands with various goals, qualities, and sampling point arrangements frequently suffer from substantial data loss; the integration and filling of big data processing techniques, such as machine learning, can bring disparate data sets together and organize them;
(3) Data pushback and its supplementary sampling technology: by combining historical sampling points with publicly available information on meteorology, soil, land use, etc., to perform data pushback and optimize encryption accuracy, it is possible to produce data quickly and affordably with high temporal and spatial accuracy for diagnosing cultivated land;
(4) Data association law mining technology, utilizing the structural equation, symbiotic network, causal inference, knowledge map, and other techniques to mine the primary and secondary relationships of cultivated land quality components.

3.3. Diagnostic and Evaluation Technologies of Cultivated Land Quality

The most important step in progressing cultivated land quality system cognition from concept to practice is the development of cultivated land quality diagnosis and evaluation, which is the process of processing, integrating, abstracting, and synthesizing the cultivated land quality ontology based on professional knowledge to form a quantitative expression of the cultivated land quality condition [42]. Accurate diagnosis and evaluation necessitate index selection, scale selection, analysis unit selection, threshold determination, and other considerations, mostly including the following analytical technologies:

(1) Index clustering and dimension reduction analysis technology: integrating the fundamental ideas of the formation of cultivated land quality and the link between element data to eliminate redundant information;
(2) Optimal scale inference technology: large data processing technologies such as machine learning have unique advantages in multi-scale spatio-temporal data processing, as they can efficiently extract features of various scales and explain them in an easy-to-understand manner;
(3) Analysis unit clustering zoning technology: the zoning analysis may more effectively highlight the impact of important indicators by taking into account the geographical variation of cultivated land quality factors;
(4) Minimum dataset construction technology: strengthening the indicator system's assessment aim orientation, phenomenon problem orientation, and scenario demand orientation;
(5) Multi-scale indicator threshold detection technology: using logistic regression, random forest, and other techniques on continually accumulating data on cultivated land quality to achieve the quick and dynamic classification of key indicators.

3.4. Simulation and Prediction Technology of Cultivated Land Quality

In addition to serving the present and predicting the future, the goal of cultivated land quality cognition is to provide decision-making plans for the governance, management, and restoration of cultivated land. Construction of cultivated land quality models, simulation and prediction, and auxiliary decision-making have all benefited from the quick development of observation [43,44] and experiment technology, high-performance computing, and big data [19]. The following elements can be specifically included:

(1) The spatio-temporal evolution model and fine analysis technology of cultivated land quality: deepening from a conceptual model to quantitative expression;
(2) The authenticity testing technology of spatiotemporal findings of cultivated land quality: improving and resolving the systematic deviation of cultivated land quality cognition brought on by the absence of representativeness of multi-scale, multi-scene, and sample sites;
(3) The intelligent early warning technology of degraded farmland: by utilizing big data, data mining, data assimilation, and other techniques, the model's real-time prediction capability and forecast accuracy are continuously improved;
(4) The auxiliary decision-making technology of cultivated land quality management: meeting the demands of social reality and management decision-making, such as resource allocation, agricultural production, farmland building, and farmland maintenance and protection.

4. Construction of Comprehensive Cognition and Evaluation System of Cultivated Land Quality in Northeast Black Soil Region

The northeast black soil region, which has 538 million mu of arable land and produces 1.4% of the nation's total grain output, is one of the "three largest black soil regions" in the world [45]. In general, the last 20 years have seen a reduction in the quality of cultivated land due to "thinning", "soil fertility lowering", and "hardening" of cultivated land due to the long-term usage of cultivated land with high input and high output. Departments of natural resources, agriculture and rural areas, ecological environment, and other scientific research institutions, including the Chinese Academy of Sciences, have committed a significant amount of manpower and material resources to the investigation and monitoring of cultivated land quality in this black soil region. They have also gathered a significant amount of historical data. Therefore, to support the preservation and enhancement of cultivated land quality in the black soil region, it is necessary to integrate and build a cognition system of cultivated land quality based on big data, as well as to conduct multi-factor and multi-structure collaborative research and judgment.

4.1. *Cognition of Cultivated Land Quality System in Black Soil Region*

Given the primary issues with the quality of cultivated land in black soil, such as a lack of a cognitive system, an imperfect evaluation index system of cultivated land quality, unconventional cooperation technology of multi-source data, and so forth, this study created a more systematic cultivated land quality evaluation system with the production function of cultivated land as the core, natural resources as supporting evidence, soil properties as the basis, farmland infrastructure construction and cultivated land ecosystem health as the guarantee, and the economic, social, and external environment as the effect (Figure 4). More specifically, by performing traditional soil profile description and analysis, historical sample analysis, and supplementary sample analysis, as well as using aerospace remote sensing, in situ monitoring of ground sites, and other data processing methods, such as machine learning and artificial intelligence, the system could uncover the relationships between cultivated land quality components and evaluate the spatiotemporal evolution process of cultivated land quality, among other things. The productivity-based multi-scale adaptability and application scenarios of the cultivated land quality evaluation index system can assist to create a comprehensive system of cognition and management that spans phenomena and essence, science and decision-making.

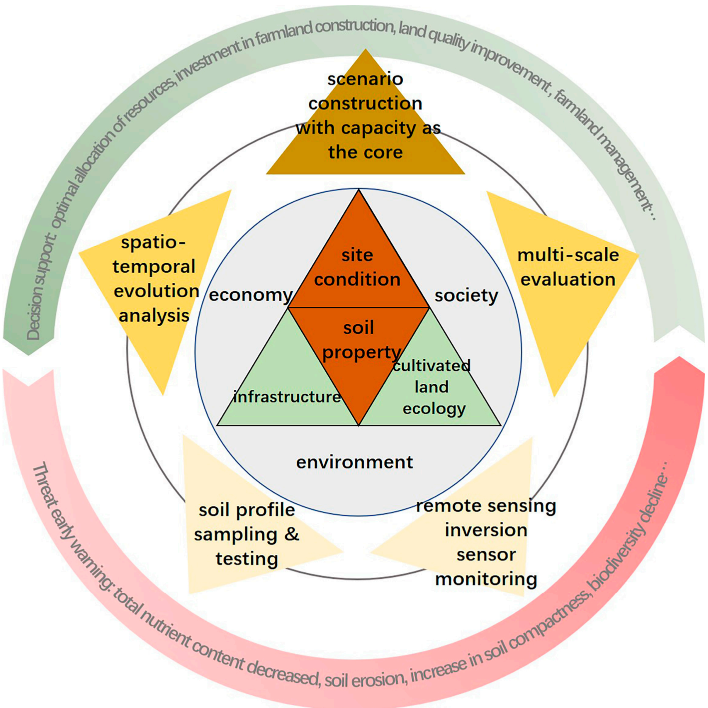

Figure 4. The cognitive framework of cultivated land quality in the black soil region. The triangle of the innermost circle represents the component of cultivated land quality. The triangle of the second circle represents different measures and methods to recognize the quality of cultivated land. From top to bottom, it represents the change of research perspective, namely: large scale of governments/authorities representative, medium scale of businesses/regions representative, small scale of farmers/farms representative. The arrow representing the outermost circle can provide decision support for cultivated land use and threat warning for cultivated land quality by analyzing cultivated land quality.

4.2. *Evaluation Index System of Cultivated Land Quality in Black Soil Region*

The northeast black soil region is one of the most significant functional areas for the production of grains in China, and the quality of its arable land should primarily represent the production potential and sustainability of that land. This paper reviewed the literature in recent years and the national cultivated land quality evaluation index system. It was found that the quality evaluation of cultivated land is no longer limited to the production function. The existing cultivated land quality evaluation focuses more on the multi-functional evaluation of cultivated land, such as ecological maintenance, threat control, and environmental protection [46–49]. This study took the black soil region of Northeast China as the evaluation target and focused on the quality function of cultivated land. The collected literature was summarized and sorted out (Table 1) and divided into seven functions: production supply, threat control, farmland infrastructure regulation, cultivated land ecological maintenance, economics, social culture, and environmental protection [7–9,16,18,46–62].

Table 1. Literature review of cultivated land quality evaluation function.

Function	Implication	References
Supply of production	Ensure the ability of cultivated land to produce enough food, vegetables, and fruits.	abcdefgijor
Threat control	Natural factors affecting or reducing cultivated land production and use efficiency.	ijklmop
Adjustment of infrastructure	Infrastructure to ensure the production capacity of cultivated land, such as field roads, irrigation and drainage facilities, power facilities.	acijorv
Ecological maintenance of cultivated land	The process of maintaining the normal operation of cultivated land system and the stability of ecological service function.	behnpstuv
Economic input	The economic cost of input in the process of cultivated land use and production, such as agricultural machinery, fertilizer, etc.	acgnoqr
Social culture	Social and cultural activities supported by arable land.	cijno
Environmental Protection	Ability to ensure the safety of cultivated land and its surrounding environment.	bcdet

(a) Regulation for gradation on agricultural land quality. (b) Cultivated land quality grade. (c) Regulation for classification of agriculture land. (d) Specification for cultivated land quality division. (e) Detailed rules for index division of arable land quality. (f) Evaluation technology standard for black soil fertility of farmland. (g) Technical rules for monitoring of environmental quality of farmland soil. (h) Comprehensive Assessment of Soil Health. (i) A Framework for Land Evaluation. (j) Feslm: An International Framework for Evaluating Sustainable Land Management. (k) The Muencheberg Soil Quality Rating (SQR). (l) Land evaluation standards for land resource mapping. (m) Risk assessment methodologies of soil threats in Europe. (n) Theoretical understanding and research trend of cultivated land quality based on factor–process–function. (o) Evaluation index system of cultivated land quality and its development trend based on cultivated land elements. (p) The current research progress and prospects of cultivated and grassland soil health—A Review. (q) Characterization of soil quality: Physical and chemical criteria. (r) Soil ecosystem profiling in the Netherlands with ten references for soil biological quality. (s) Active microorganisms in soil: critical review of estimation criteria and approaches. (t) Prioritizing soil quality assessment through the screening of sites: the use of publicly collected data. (u) Selection of biological indicators appropriate for European soil monitoring. (v) Soil Quality–A Critical Review.

With cultivated land production capacity as its heart, the functions of cultivated land in this paper (Table 1) were determined in accordance with the fundamental framework of the "foundation-guarantee-effect" of cultivated land quality, in addition to the current condition of cultivated land use in the black soil region of Northeast China.

In this study, an index system for assessing the quality of cultivated land on black land is constructed in accordance with the fundamental principles of "dominance, simplicity, and easy access" (Table 2). This paper summarized the evaluation system of cultivated land quality in recent years, and determined the evaluation system as 3 parts, 7 aspects, and 20–31 indicators (Table 2), and classifies the quality of cultivated land by assignment, comprehensive scoring, and grading. The evaluation's findings mostly represent the quality of cultivated land over a lengthy period and are highly correlated with long-term average crop productivity. It is appropriate for cultivated land quality assessments at the county and farmland agricultural unit levels, and regional cultivated land quality assessments can also be used as a guide.

Table 2. Index system of cultivated land quality evaluation in black soil region with productivity as the core.

	Function	Key Process	Key Indicators	Alternative Indicators
Foundation	Supply of production	Production of material	Grain per unit yield	Root density
		Conversion of energy	Accumulated temperature illumination	Slope of terrain
		Cycle of Matter	Soil texture	Nutrient of soil
		Hydrological cycle	Rainfall precipitation	Depth of underground water table
		Transmission of information	Incidence of pests and diseases	Pesticide application amount
	Threat control	Erosion of soil	Effective root depth	
		Nutrient content decreased	Soil organic matter	Annual soil nutrient changes
		Compaction of soil	Soil compactness	Soil bulk density
Security	Adjustment of infrastructure	Leveling of land	Field shape	The thickness of the plowing layer
		Agricultural water control	Water-saving irrigation ratio	Soil drainage capacity
		Farmland protection	The density of forest net	
		Post-management and protection	Average management and protection input per mu	
	Ecological maintenance of cultivated land	Self-purification	Annual change of hazardous substances	
		Self-regulating recovery	Soil biodiversity level	
Effect	Economic input	Production input	Input cost per mu	Fertilizer application amount
		Use of agricultural machinery	Degree of mechanization	
	Social culture	Land circulation	Average business scale	Land transfer rate
		Production organization	Social service level	
	Environmental Protection	Transfer of harmful pollutants	Content of harmful substances in agricultural products	
		Formation of landscape	Level of ecological landscape diversity	

4.3. Application Scenario Analysis of Cultivated Land Quality in the Black Soil Region

Currently, the knowledge of cultivated land quality of the black soil region may satisfy a number of demands and be applied to a variety of scenarios, such as government management, market participants, and farmers (Table 3). The main goals are to fulfill decision-making needs, concentrating on regional resource optimization, farmland building project arrangement, farmland quality enhancement technology, agricultural machinery socialized service, farmland farming management, etc. More particularly, in the application scene with management as the requirement, the inquiry and assessment are concentrated on various areas of cultivable land quality in accordance with the present needs of natural resources, agricultural output, and ecological environment management. Large-scale agricultural firms and social service organizations make up the bulk of the market, and both have a need to identify more effective production management models and service programs, such as agricultural machinery and agronomy, through an understanding of cultivated land quality. Farmers and farms make up the two categories of the primary production, and there are several approaches for paying attention to the quality of the cultivated land.

Table 3. Cognitive application scene of cultivated land quality in the black soil region.

Scene	Main Participant	Key Goal	Cognitive Demand for Cultivated Land Quality
Government management	Local government	Status of regional cultivated land resources	Present situation and changing the trend of cultivated land quality
	Natural resources department	Allocation of quality elements of cultivated land	Site conditions and utilization of cultivated land
	Agricultural and rural department	Crop yield	Cultivated land productivity and agricultural product safety
	Ecological and environmental department	Cultivated land ecological environment	Ecosystem stability and environmental impact
Market	Production enterprise	Cultivated land income	Cultivated land capacity, farmland infrastructure, production cost, quality of agricultural products
	Service enterprises	Socialized services such as agricultural machinery	Farmland infrastructure, suitable planting patterns, and application configuration of agricultural machinery
Production	Farmers	Stability of cultivated land production	Cultivated land productivity, the cultivated land quality threat, cultivated land adjustment ability
	Farm	Operation scale of cultivated land	Cultivated land productivity, production organization, production cost

4.4. Technical Challenges to the Cognition of Cultivated Land Quality in the Black Soil Region

At present, there are still some technical challenges to a comprehensive understanding of the quality of cultivated land in black soil regions. Using the cognitive framework of the cultivated land quality system from the data perspective and focusing on the cognitive goal and research content of black soil cultivated land quality, emphasis should be given to the use of space–air–ground integrated data acquisition technology, ground rapid investigation and in situ monitoring technology, and new cultivated land quality index detection technology to obtain soil profile, soil detection index, remote sensing information, and other data. Additionally, in order to model and predict the missing year and missing index data, as well as to collect the cultivated land quality data for the entire time series and the entire region, it is important to build incomplete data integration and filling technology. To obtain the key cultivated land quality indexes of black soil site conditions, profile characters, soil health, and productivity, it is necessary to develop traditional soil science methods in conjunction with index clustering and dimensionality reduction analysis techniques. It is also necessary to build a big data platform for black land cultivated land quality evaluation in order to create a multi-structure black land cultivated land quality list for various users.

5. Conclusions

A blend of natural and artificial elements determines the quality of land used for agriculture. Humans now have more tools to perceive the qualities of cultivated land, which has facilitated the development of multidisciplinary cultivated land cognitive infrastructure and contributed to the generalization of the meaning of cultivated land quality. In the black soil region of Northeast China, the last 20 years have seen a reduction in the cultivated land quality due to “thinning”, “soil fertility lowering”, and “hardening” of cultivated land, which threaten the health of cultivated land. It is urgent to analyze the quality of cultivated land based on the data perspective. Against these issues, this paper examined the conceptual model of cultivated land system cognition from the perspective of data, combined the fundamental components and theoretical approaches of cultivated land quality cognition, and attempted to build a big data cognitive analysis technology system of cultivated land quality based on the principle of data value transformation. Big data technology has been listed as an important breakthrough direction of evaluation research by many related disciplines, and so has the research on cultivated land quality evaluation. Our research is also based on the data perspective to establish the framework of cultivated land quality analysis. By utilizing this framework, we investigated and developed the cultivated land quality evaluation system in the black soil region of northeast China, analyzed its application scenarios, and highlighted key supporting technologies. This study demonstrates the framework's good adaptability, expansibility, and maneuverability. However, further research is needed to verify the application effect of the theory and method.

In the future, we will focus on the practical cases of the application of this framework in the black soil region of northeast China, mainly focusing on multi-time, multi-scale, multi-attribute, and multi-objective multi-dimensional investigation of cultivated land quality, big data technologies, such as incomplete data integration and filling, data regression and supplementary sampling, index clustering and dimension reduction analysis, evaluation methods in different scenarios, such as farmers, farms, businesses, regions, and governments, and the relationship between cultivated land quality and productivity, etc., so as to form a systematic and scientific cognitive and analytical technology system of cultivated land quality in the black soil region of northeast China. The study shows that the analysis framework constructed in the paper provides valuable insights for systematic cognition and evaluation of cultivated land quality.

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