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Accessibility Assessment of the Iron Deposits on the Qinghai–Xizang Plateau: Integrating Transport Networks, Economic Dynamics, and Ecological Constraints

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Abstract: The Qinghai–Xizang Plateau (QXP) is the highest plateau on Earth, with a significant quantity of iron resources that significantly contribute to regional economic development in Western China. However, the exploitation of these iron deposits on the QXP is confronted with dual challenges. The complex geography and weak infrastructure lead to inadequate transport accessibility, while the strict ecological regulations and stringent environmental protection policies further complicate resource development. This study focuses on the transport accessibility issues related to iron deposits on the QXP, aiming to assess the suitability for regional iron resource development. This study conducts a comprehensive, multidimensional analysis encompassing the spatial distribution of iron deposits, the characteristics of the transport network, and economic dynamics. Based on these analyses, an integrated suitability evaluation model is developed to assess the accessibility of iron deposits on the QXP. The results indicate that the transport accessibility of iron deposits on the QXP displays obvious spatial disparities. The deposits on the western QXP exhibit lower accessibility due to the remoteness from major economic centers and underdeveloped transport infrastructure. In contrast, the deposits on the eastern QXP, which are closer to transportation and economic centers, show greater development potential. Additionally, this study innovatively incorporates economic dynamics and ecological protection factors into the transport accessibility evaluation framework, revealing the coupling relationship between the transport conditions, economic patterns, and mineral resource development potential. It provides scientific evidence for the balancing of resource development and environmental protection in ecologically sensitive areas. The findings could contribute to optimizing the iron resource development strategies on the QXP and provide theoretical support for future regional infrastructure planning.

Keywords: Qinghai–Xizang Plateau; iron resource; transport accessibility; suitability evaluation; ecological protection; regional economy

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1. Introduction

Iron, as a critical raw material for modern industry and global economic infrastructure construction, plays a pivotal role in driving regional economic growth and advancing

sustainable development [1,2]. With the accelerated pace of global industrialization and urbanization, the demand for iron resources continues to surge, while the constraints imposed by environmental protection and ecological safety policies grow increasingly stringent [3]. This dual challenge exacerbates the complexity of mineral resource development. On the Qinghai–Xizang Plateau (QXP), a region rich in iron resources, the development potential and economic benefits are severely constrained by the complex natural geographic conditions, underdeveloped transportation infrastructure, and stringent ecological protection policies [4]. Iron's lower unit value compared to metals such as copper and lead renders its development heavily influenced by the transportation costs [1]. To mitigate the logistical expenses and enhance the economic efficiency [5], iron ore beneficiation and smelting operations are typically prioritized near consumption centers [6]. However, the QXP's high-altitude terrain and remoteness from major ports pose formidable challenges to local iron resource exploitation [7]. Elevated transportation costs and logistical bottlenecks further hinder the importation of external iron resources [8]. Additionally, although China possesses abundant iron reserves, the lower grades of some ores significantly increase the long-distance transportation costs, impairing the smelting efficiency and product quality, thereby undermining their economic viability [1]. Against this backdrop, rational spatial layout planning for iron ore development—particularly optimizing transport accessibility—has become essential for efficient and cost-effective resource utilization [9].

Recent advances in mineral resource development suitability research have focused on optimizing transportation networks and leveraging synergistic effects in resource exploitation [10,11]. Enhancing the transportation infrastructure is widely acknowledged as a key strategy to reduce the development costs and improve the regional resource utilization efficiency [12]. For instance, studies on mineral resource development in Africa and South America demonstrate that infrastructure improvements lower logistics costs and enhance resource market competitiveness [13]. Concurrently, increasingly stringent ecological protection policies have propelled the green mining model as a critical future development paradigm [14]. Research on iron resources in the QXP has evolved from single-factor analyses to multidimensional evaluations [6], with studies [15] highlighting the pivotal role of transportation networks in resource development. Investigations into transport accessibility patterns across the QXP reveal that shifts in the regional transportation network since the 1970s have profoundly reshaped the spatiotemporal distribution of resource exploitation [7,16]. Furthermore, empirical evidence underscores the significant positive correlation between the transportation conditions and resource development efficiency [17], with the interplay of regional policies and transportation networks imposing substantial constraints on mineral resource development [18].

Developing mineral deposits in remote and hard-to-reach areas is often considered uneconomical due to challenging natural conditions and high infrastructure costs. However, failing to develop these areas can have significant ramifications. It limits the supply of critical minerals, undermines long-term economic stability, and restricts future growth. Moreover, it exacerbates socioeconomic issues in these regions, hindering improvements in local living standards and economic conditions. Although some studies have explored the transport network and mineral resource development on the QXP, most studies have focused on resource reserves or single transportation condition analysis, lacking a comprehensive evaluation integrating multiple factors [19]. Therefore, there is an urgent need to conduct a more integrated and systematic resource development suitability study that combines the unique geographical environment, infrastructure conditions, and ecological protection policies of the QXP. This study introduces a multidimensional approach to accessibility evaluation that integrates not only transport accessibility but also economic and environmental factors. This study proposes a comprehensive approach to assessing

the accessibility of iron deposits on the QXP by integrating three key dimensions: transport accessibility, regional economic feasibility, and environmental constraints. Unlike conventional accessibility assessments that primarily focus on transport networks, this study expands the scope by considering economic and environmental factors, ensuring a more realistic evaluation of a deposit's potential for development. Specifically, this study develops a transport accessibility model based on the road network, calculates the average shortest path distance from the deposits to 39 major cities in and around the QXP, and evaluates the impact of the transport conditions on the economic feasibility of mining development based on regional economic data. Additionally, this study explores the constraints imposed by ecological protection policies on mining spatial distribution and development prioritization. By quantitatively analyzing the impact of transport infrastructure optimization in different regions on the development potential, this study identifies priority development areas for iron resources on the QXP. This study fills a gap regarding the suitability evaluation of iron resource development on the QXP. It provides scientific decision support for the balancing of resource development and ecological protection in plateau regions. This study also offers an important reference for resource development in other ecologically sensitive areas with significant theoretical and practical value by applying a multidimensional evaluation model.

2. Materials and Methods

2.1. Study Area

The QXP, located in the southwestern part of China, spans across the Xizang Autonomous Region [20], Qinghai, and parts of Sichuan, Yunnan, and Gansu, covering an area of approximately 2.5 million square kilometers. It is the highest plateau in the world, often referred to as the "Roof of the World" (Figure 1) [4,21]. This region holds global significance in the Earth's ecosystem and is also an important site for iron resources in China [15]. The iron resources on the QXP are characterized by their wide distribution and substantial reserves [22]; however, the region's complex geographic environment, relatively weak infrastructure, and stringent ecological protection policies significantly constrain resource development [23]. Mining areas are primarily located at high altitudes, where the challenging terrain and climatic conditions make infrastructure construction and transportation particularly difficult [24]. Furthermore, several mining areas are within national ecological reserves, subject to strict environmental regulations, which further limit mining development's spatial extent and scale [25]. This study focuses on the distribution and development suitability of medium- and large-scale iron deposits within the QXP. In contrast, small-scale iron deposits are excluded due to their limited economic viability. Figure 1 illustrates the distribution of the mining sites and the road network in the region, providing essential spatial information for the study.

2.2. Data

This study integrates multiple data sources to support the analysis. The target city data include 39 major cities within and surrounding the QXP, which serve as the primary consumption markets and processing hubs for iron resources. These cities include regional economic centers such as Xining and Lhasa and national transportation hubs like Chengdu and Lanzhou. Traffic network data, sourced from publicly available mapping resources, include road and railway information for the QXP and its surrounding areas, providing essential support for the quantification of the accessibility of mining sites to the target cities. Mining data encompass the location, reserve size, and ore type characteristics of the deposits, sourced from relevant academic papers, geological survey reports, and mining investigations, ensuring the scientific validity and authority of the data. This study mainly

focuses on medium, large, and extra-large iron deposits and, through the integration of multidimensional data, provides systematic data support for the development of the iron resources on the QXP. Detailed information about the data sources is provided in Table 1.

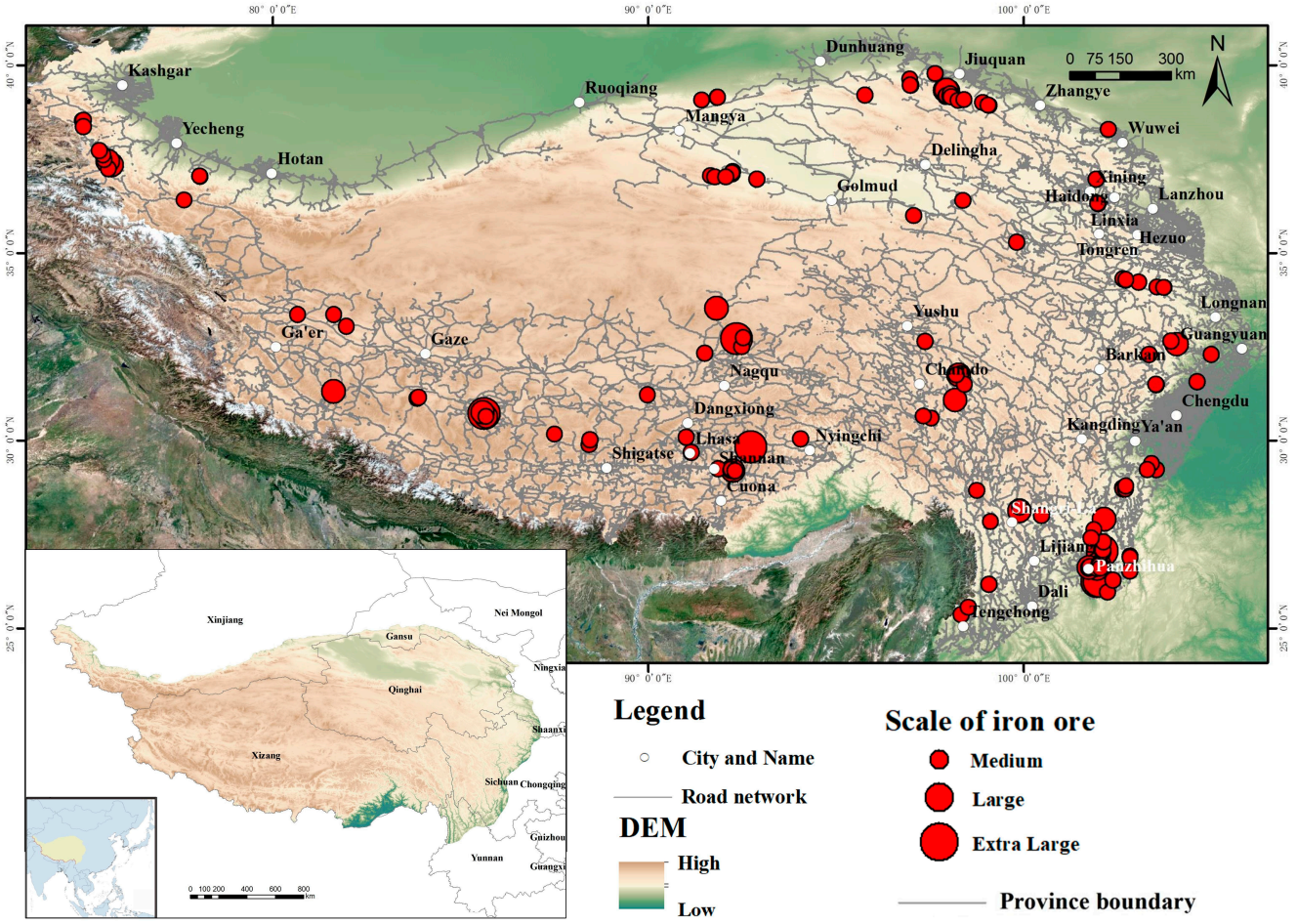

Figure 1. Spatial distribution of iron deposits and transportation networks including roads and railways on the QXP. Thirty-nine major cities serve as economic hubs. The background topography, represented by a digital elevation model (DEM), highlights the plateau's unique high-altitude geography.

Table 1. Data sources and details for the QXP study.

Data	Scale	Time	Original Data Resource
Road network	Vector data	2023	Traffic road data from Open Street Map (https://www.openstreetmap.org, accessed on 15 October 2024).
Iron ore mines	Deposit		Organized and evaluated based on data from the S&P Global Market Intelligence database (https://www.capitaliq.spglobal.com, accessed on 15 October 2024), the National Mineral Resources Survey Project (2007–2012), and the pan-tertiary geology and mineral map from ref. [25].
Ecological reserves	Vector data	2024	Nature reserves published by the Ministry of Natural Resources and the Ministry of Ecology and Environment of China (https://www.tpdc.ac.cn/home, accessed on 15 October 2024).
DEM data	30 m	2021	Publicly available data from the National Qinghai–Xizang Plateau Science Data Centre (https://data.tpdc.ac.cn/zh-hans/data, accessed on 15 October 2024) [26].
GDP data	County	2022	Data from the 2022 China County Statistical Yearbook (County and City Volume) published by the National Bureau of Statistics (NBS).

2.3. Methodology

Transport accessibility is assessed based on the shortest travel distance from each iron deposit to major cities, reflecting the logistical feasibility of resource transportation. Economic feasibility is incorporated by referencing the regional per capita GDP, which serves as an indicator of the economic capacity to support mining activities. Third, environmental constraints are evaluated by considering the spatial overlap between iron deposits and protected areas, identifying potential legal and ecological limitations on development.

By integrating these three aspects, this study provides a multidimensional evaluation framework that offers a more precise and applicable assessment of iron deposit accessibility, as shown in Figure 2. The following sections detail the methodologies used for each component: transport accessibility [27,28], economic feasibility, and ecological constraints.

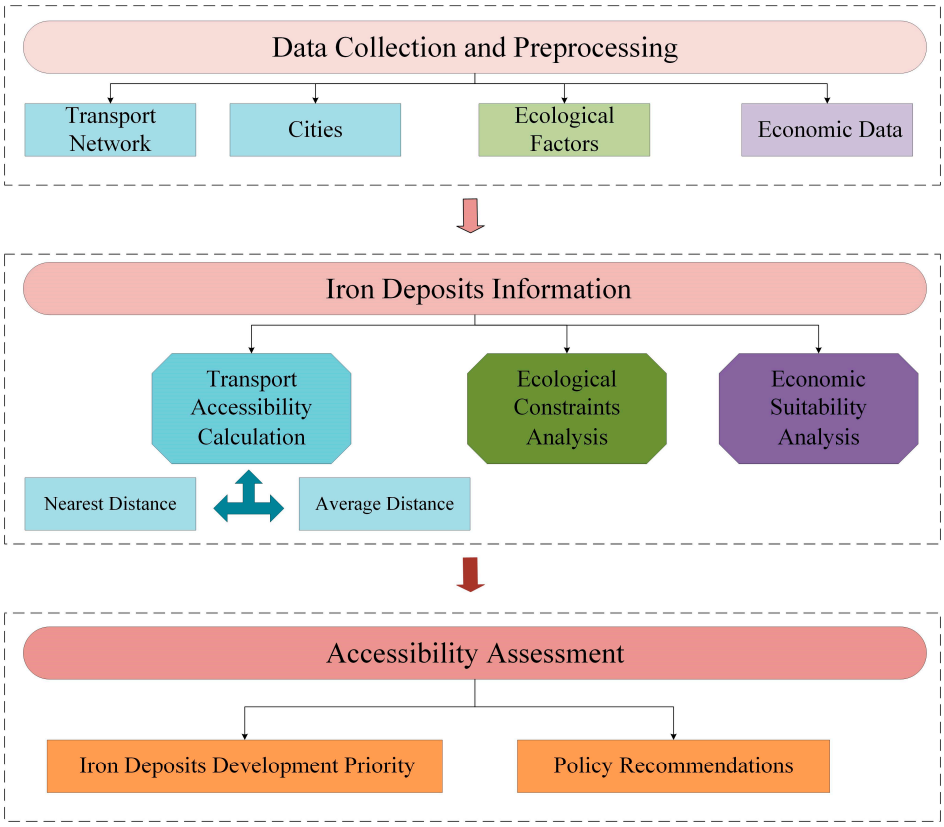

Figure 2. Multidimensional evaluation framework that offers a more precise and applicable assessment of iron deposit accessibility.

2.3.1. Transport Accessibility

The core objective of this study is to assess the development suitability of the iron deposits on the QXP, with a particular focus on the impact of transportation accessibility on iron ore development. In the QXP region, the development of iron ore is constrained by the transportation conditions [29]. Due to the relatively low price and high demand for iron ore, transportation costs play a significant role in the entire development process [1]. Therefore, transportation accessibility becomes the primary evaluation indicator for this study [30]. Furthermore, this study considers only the transportation distance factor and does not involve the impact of road classifications, vehicle speed limits, or other factors on accessibility.

This paper mainly adopts the distance accessibility model and uses the shortest path algorithm to calculate the minimum transportation distance from mines to major cities, thereby evaluating the transportation accessibility. Accessibility, also referred to as reach-

ability or ease of access, originates from classical location theory and is a quantitative measure of the regional transportation advantage or potential [31]. It is widely regarded as one of the fundamental conditions for regional economic development. Harris [32] first applied the market potential model, integrating land and water transport, to measure market accessibility and argued that transportation accessibility was a crucial factor influencing the development of domestic manufacturing in the United States. Subsequently, Hansen [33] proposed a definition of accessibility, describing it as the magnitude of interaction opportunities among nodes in the transportation network. The prevailing view is that accessibility refers to the ease or difficulty in reaching a particular location [34]. Accessibility models mainly include distance accessibility, opportunity accessibility, economic accessibility, and gravity models based on spatial interactions.

In this study, a distance accessibility model is adopted. The basic assumption of this model is that transportation costs are solely related to the transportation distance and ore weight and are independent of the transportation time, road classifications, or vehicle speed limits. Iron metal has a relatively low price but high demand, making the transportation costs particularly significant in terms of development costs [35]. The transportation distance is the primary factor affecting the transportation costs, while other factors contribute relatively little to the overall development costs [36]. Therefore, this study chooses the transportation distance as the sole criterion for the measurement of transportation accessibility.

In calculating the transportation accessibility, this study relies on the shortest network distance from each mine to 39 target cities, calculating the average accessibility distance for each mine. This method allows for a quantitative assessment of the impact of the transportation conditions on the development suitability of the iron deposits on the QXP, we further analyze the development potential of different mines under the current transportation network conditions. To achieve this goal, this study utilizes the shortest path algorithm to calculate the shortest transportation distance from medium and large iron deposits on the QXP to surrounding cities [37]. This approach enables a quantitative analysis of the impact of transportation accessibility on iron resource development and further reveals the accessibility pattern of the iron ore on the QXP [38]. To calculate the network distance from a mine to a city via the road network, this study constructs a transportation network map, where

Nodes represent the locations of iron deposits and target cities;

Edges represent the transportation paths between nodes, with edge weights defined as the path distance based on actual roads.

Let $G = (V, E)$ represent the transportation network graph, V the set of nodes, and E the set of edges. The weight d_{ij} of each edge is defined as

$$d_{ij} = \text{Road network distance}(i, j) \tag{1}$$

where $i, j \in V$ and $d_{ij} > 0$. If there is no direct path between nodes i and j, then let $d_{ij} = \infty$.

To further assess the accessibility of mines to various target cities, this study employs the shortest path algorithm. The shortest path algorithm is a classical graph theory algorithm used to calculate the shortest path between two points in a graph [39]. In this study, the nodes in the network graph represent the mines and target cities, while the edges represent the transportation paths between them. The Dijkstra algorithm is employed to solve the single-source shortest path problem [40]. This algorithm efficiently solves the shortest path problem in weighted graphs and is particularly suitable for calculating the shortest paths between multiple nodes in the complex transportation network of the QXP [41,42].

The basic idea of the Dijkstra algorithm is as follows: starting from the source node (i.e., the mine), the shortest path to all other nodes (target cities) is calculated sequentially [43]. The algorithm continuously updates the shortest path for each node until the shortest paths to all nodes are determined [44,45]. Since the transportation network between mines and target cities is constrained by the existing road conditions, the use of this algorithm ensures that the most accurate shortest transportation distances are obtained.

For each mine i, the shortest path distance to all target cities j is calculated as d_{ij}, as shown in Equation (2):

$$d_{ij} = \min\left(d_{ik} + d_{kj}\right), \forall k \in V \tag{2}$$

where d_{ik} and d_{kj} represent the path distances from mine i to the intermediate node k and from node k to the target city j, respectively.

The average accessibility distance for each mine i is calculated using the following formula (Equation (3)):

$$D_i = \frac{1}{N}\sum_{j=1}^{N} d_{ij} \tag{3}$$

where N is the number of target cities (in this study, N = 39); d_{ij} is the shortest path distance from mine i to city j. The average accessibility distance D_i represents the overall transportation convenience of mine i. A smaller value indicates better transportation conditions for the mine and lower development transportation costs.

To facilitate a comparison between mines, this study converts the average accessibility distance (or the nearest city distance) into an accessibility score S_i, using the following formula (Equation (4)):

$$S_i = \frac{D_{\max} - D_i}{D_{\max} - D_{\min}} \tag{4}$$

where $D_{\max}$ is the maximum average accessibility distance (or maximum nearest city distance) among all mines; $D_{\min}$ is the minimum average accessibility distance (or minimum nearest city distance) among all mines; and S_i is the accessibility score, with a range of [0, 1], where a higher value indicates better transportation conditions.

The accessibility score standardizes the transportation advantages of different mines, making the development suitability evaluation more intuitive and comparable.

2.3.2. Economic Feasibility

To incorporate economic factors into the accessibility assessment of iron deposits, this study analyzes the spatial relationship between transport accessibility and regional economic development [46]. The per capita GDP is selected as a key indicator to reflect the economic capacity of different regions to support mining activities. A higher per capita GDP generally indicates better-developed infrastructure, financial resources, and market accessibility, which can lower the economic barriers to resource exploitation. Conversely, in regions with a lower per capita GDP, high logistical costs and weak economic activity may hinder mining feasibility.

The methodology involves spatial analysis that overlays transport accessibility data with the regional per capita GDP. By mapping and comparing these two factors, this study identifies areas where high accessibility aligns with strong economic conditions, as well as regions where economic constraints may impede mining development despite favorable transport accessibility. This spatial correlation analysis provides insights into how the economic conditions interact with the transport infrastructure, offering a more comprehensive perspective on the feasibility of mineral resource development.

2.3.3. Ecological Constraints

This study employs spatial analysis methods to assess the impact of ecological protection policies on the accessibility of iron deposits. First, a geographic information system overlay analysis is conducted using spatial data on ecological reserves and iron deposit distributions to determine the spatial relationships between deposits and protected areas [47]. Subsequently, accessibility calculations are performed to quantify the transport accessibility of deposits, followed by a comparative analysis between deposits inside and outside protected areas to identify potential constraints imposed by ecological policies on resource development.

During data processing, this study incorporates classification information on ecological reserves to distinguish between different levels of protection and assess their varying impacts on the resource development potential. Simultaneously, considering the spatial distribution of the transport network, the shortest path distances from deposits to major economic centers are calculated to evaluate the influence of the transport infrastructure on resource accessibility.

Furthermore, to examine the role of ecological reserves in shaping regional accessibility patterns, this study investigates the spatial distribution of protected areas in relation to the transport network. By identifying potential barriers posed by ecological reserves to transport corridors, the indirect effects of ecological protection policies on deposit accessibility are assessed. Finally, an integrated analytical framework is established to support the future optimization of transport infrastructure and resource development policies, ensuring a balanced approach to mineral resource exploitation and ecological conservation.

3. Results

3.1. Regional Characteristics of Transport Accessibility

Figures 3 and 4 illustrate the distribution of the average road network distances for the iron deposits on the QXP and the shortest distances to the nearest cities. Figure 5 presents the distribution of the transport network complexity based on the road network density, reflecting the coverage capacity of the regional transport infrastructure. Together, these figures reveal significant spatial variations in the transport accessibility and network complexity of the iron deposits on the QXP.

The results demonstrate a marked spatial gradient in the accessibility of iron deposits across the QXP. An apparent increase in average accessibility is observed from the southeast to the northwest. High-accessibility regions are predominantly located in the eastern part of the QXP, which benefits from high transport network complexity and proximity to economic centers, significantly enhancing the logistical efficiency [42]. High-accessibility iron deposits typically have average distances under 200 km, mainly concentrated in the southeastern regions, such as Northwest Yunnan and Southeast Xizang, with accessibility scores generally above 0.7. Conversely, the analysis based on the shortest distances further emphasizes the economic advantages of these high-accessibility deposits, with most having an average distance to the nearest city of under 200 km (Figure 4).

In contrast, low-accessibility deposits are mainly concentrated in the northwestern region, where the average distances typically exceed 3 million meters and the accessibility scores are below 0.2. This lower accessibility is closely related to the sparse transport infrastructure and the considerable distance from major consumption markets [42]. For example, the average transport distance of the Nixiong iron deposit in Cuoqin exceeds 4 million meters, and its low score in terms of the nearest-city distance further limits its economic viability due to excessively high logistics costs. Similarly, despite its large scale, the Qiaopuka iron deposit in Taxkorgan faces severe restrictions on its development potential due to its remote location, with an average accessibility score below 0.1. Another

example is the Qierkeqi iron deposit in Akto, with an average distance of over 3.38 million meters and a score of only 0.014, highlighting the significant impact of transport costs on the development feasibility. Further analysis indicates that the low accessibility of these regions not only restricts the economic benefits of resource development but significantly lowers their development priority [44].

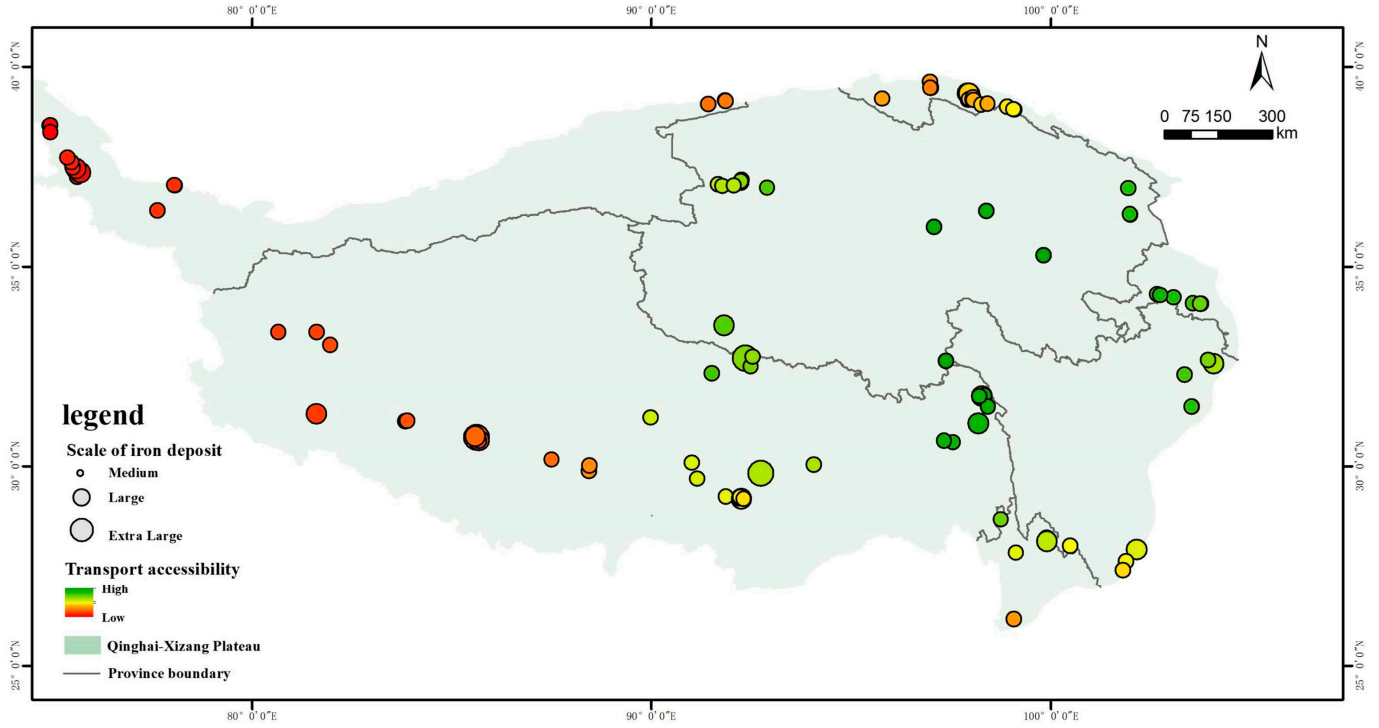

Figure 3. Transport accessibility on the QXP based on the average distance.

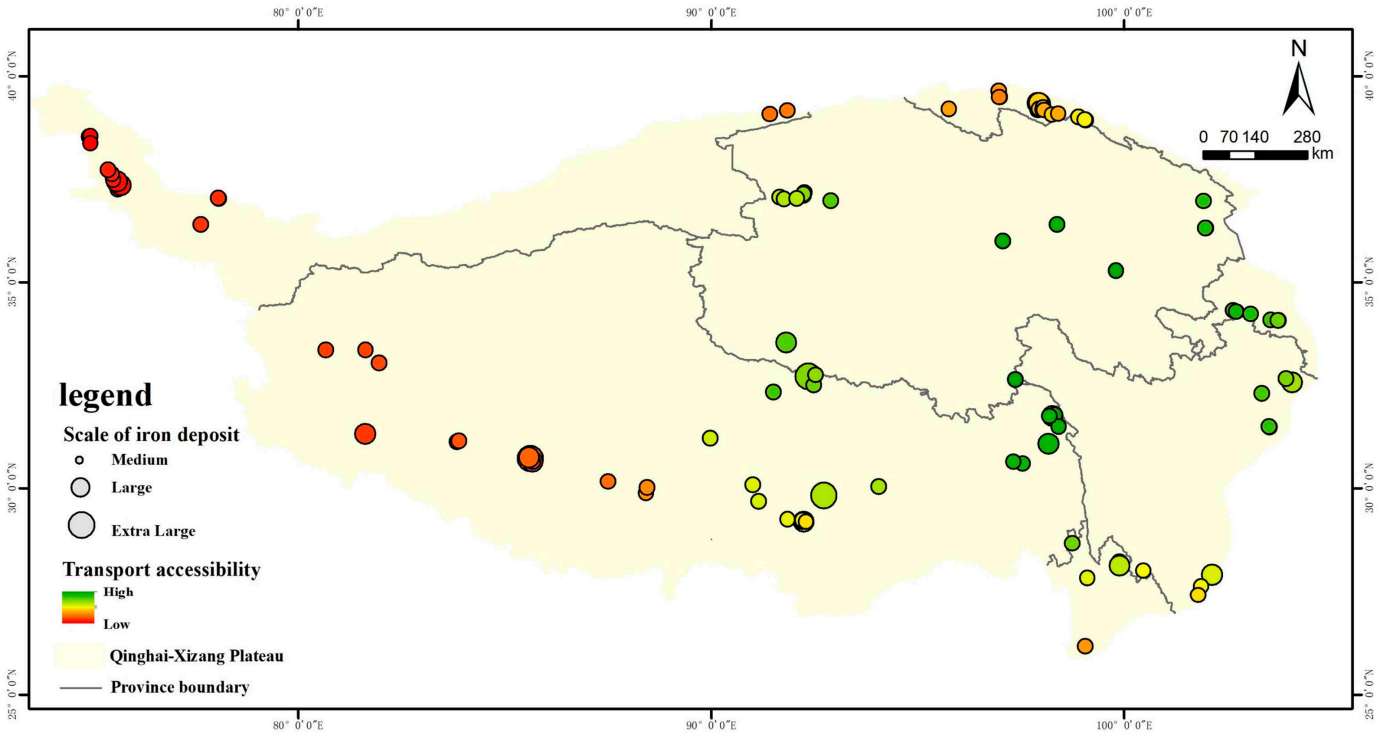

Figure 4. Transport accessibility on the QXP based on the nearest-city distance.

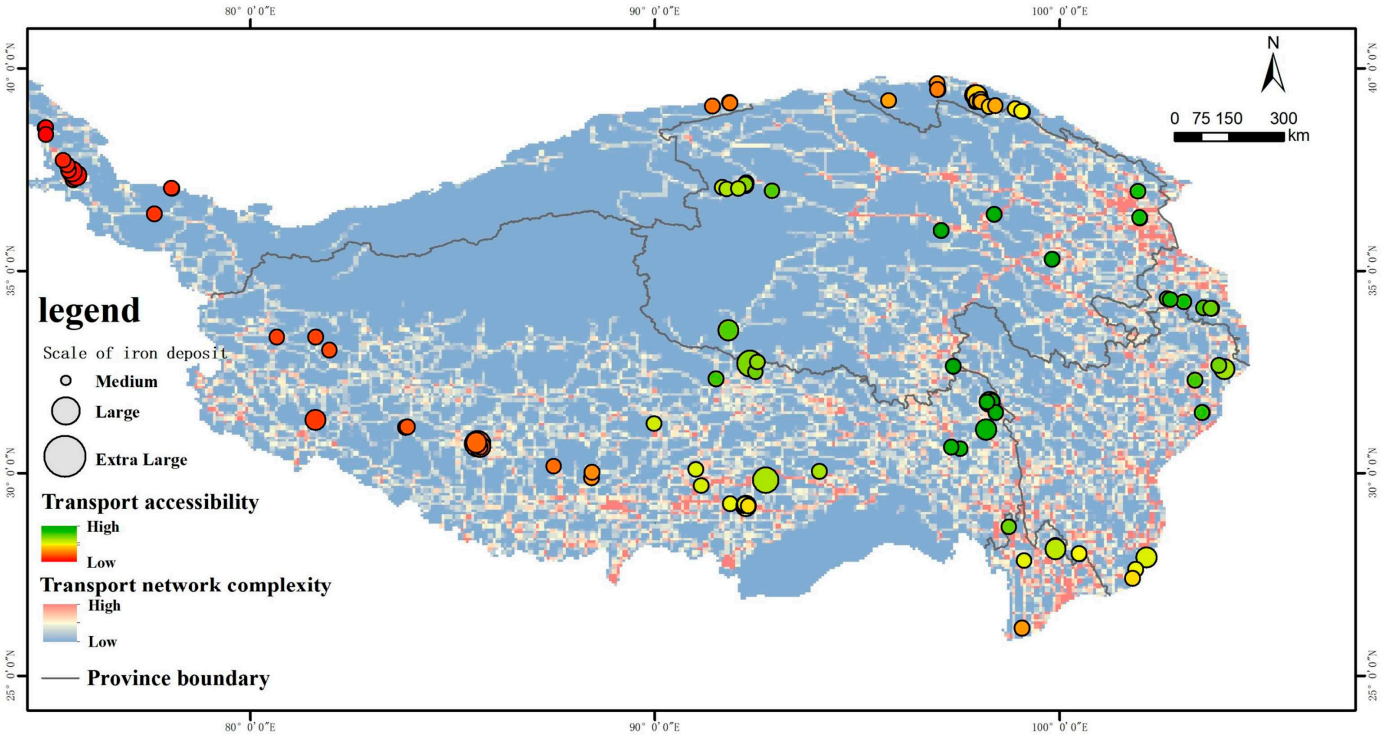

Figure 5. Transport network complexity and transport accessibility of iron deposits based on the average distance.

Figure 4 further reveals that over 70% of the deposits have a nearest-city distance of less than 300 km, predominantly in the southeastern regions, such as Northeast Sichuan, Eastern Qinghai, Northwest Yunnan, and Central Xizang. Iron deposits near major transport hubs like Shangri-La, Dali, and Lhasa generally have high accessibility scores (>0.6). Notably, deposits near Jiuquan also exhibit high accessibility scores, exceeding 0.7, due to multiple iron deposits in Gansu's Suxian. These deposits benefit from lower transport costs, significantly enhancing their development potential. Conversely, approximately 10% of the deposits have a nearest-city distance exceeding 400 km, mainly concentrated in the northwestern regions, such as Kashgar and Yecheng. These deposits, often with Yecheng as their nearest city, show low accessibility scores (<0.3), with transport limitations greatly hindering their development.

In addition, the analysis based on the average distance provides a more intuitive reflection of the logistical potential of iron deposits, especially in regions with high accessibility and network complexity. This advantage arises from the strong coupling of the transport network complexity and economic activity in Northwest Yunnan and Southeast Xizang [43]. On the other hand, the analysis based on the nearest-city distance highlights the short-haul transport advantages of deposits near important cities, such as the Liangzi iron deposit in Yanxian, which has a nearest-city accessibility score of 0.796. Although its average distance is 1.8 million meters and its average accessibility is slightly lower, it still holds significant development potential within the regional market context (Figure 4). Deposits surrounding Lhasa, due to their proximity to regional economic centers and transport hubs, exhibit high accessibility scores, exemplified by the Letingang iron deposit in Deqing Township, Duolongdeqing, with a nearest-city distance of 111 km and a score of 0.781. In contrast, deposits near Kashgar and Garch in Xinjiang, such as the Qiaopuka iron deposit in Taxkorgan, despite substantial resource reserves, face significant development constraints due to their considerable distances from the nearest city, exceeding 500 km.

In summary, the dual analysis based on the average and nearest-city distances not only reveals the spatial imbalances in the transport accessibility of iron deposits on the QXP but also provides quantitative support for the dynamic assessment of resource development priorities. Deposits in high-accessibility regions of the southeastern plateau possess significant development advantages due to their favorable transport conditions and lower logistics costs. In contrast, the development of deposits in the low-accessibility northwestern regions relies heavily on the future optimization of transport networks and infrastructure enhancement to achieve the balanced development of resources across regions. From the dual perspective of the nearest-city distance and average distance, these findings offer a scientific basis for the subsequent suitability evaluation of iron ore development and lay a solid foundation for the optimization of transport network planning and the development of strategies for the QXP iron resources.

3.2. Spatial Coupling of Transport Accessibility and Economic Development

The analysis of economic development based on the GDP per capita and transport accessibility on the QXP (Figure 6) reveals a significant coupling relationship between transport accessibility and regional economic development. The southeastern region, including Northwest Yunnan and Southeast Xizang, demonstrates higher economic activity and favorable transport conditions, with high-accessibility deposits (accessibility score > 0.7) accounting for more than 50% of the deposits in these areas. These deposits benefit from their proximity to economic centers, such as Chengdu and Lhasa, and transport hubs, significantly enhancing the logistical efficiency and increasing the development potential. For instance, the Sedirang iron deposit in Gongbujiangda, with its high accessibility score and advantageous economic location, exemplifies a priority development deposit (Figure 6).

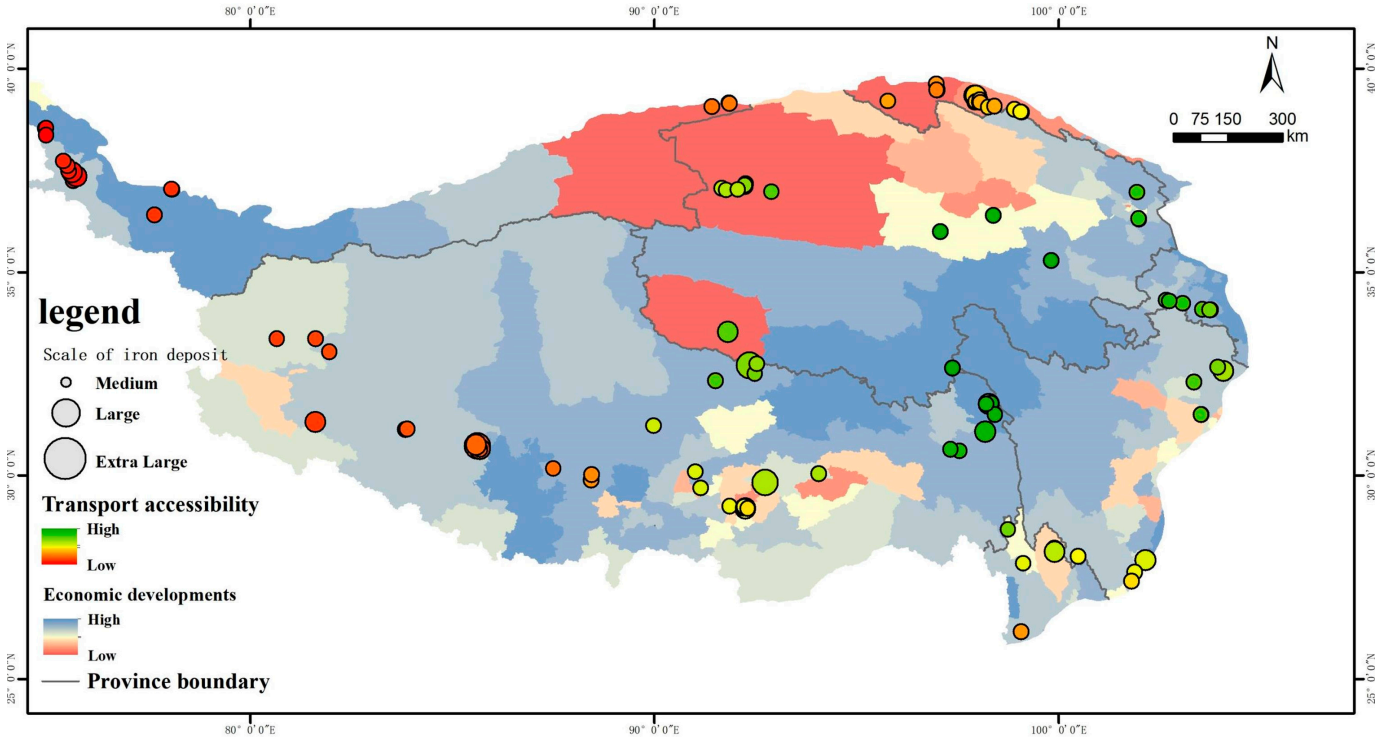

Figure 6. Spatial relationship between economic development and the transport accessibility of iron deposits based on the average distance.

In contrast, the northwestern region exhibits significantly lower levels of both economic activity and transport accessibility. Low-accessibility deposits (score < 0.3) make up more than 30% of the total deposits in this region. Areas such as Kashgar and Gaze suffer from sparse transport networks and a considerable distance from significant consumption markets, with the logistics costs exceeding 50% of the total development costs, severely limiting the economic feasibility of resource development. These areas also display a vicious cycle, where economic underdevelopment and transport isolation exacerbate each other, further diminishing the role of resource development in driving regional economic growth.

Further analysis indicates strong coupling between regional economic development and transport network complexity (Figures 5 and 6). Economically active areas, such as Northwest Yunnan and Southeast Xizang, not only have dense transport networks but also exhibit significantly higher logistical efficiency compared to other regions of the QXP, providing favorable conditions for iron resource development. In contrast, the economically underdeveloped northwestern regions, where economic disadvantages are combined with transport challenges, experience a substantial decrease in the development potential of mineral deposits, underscoring the profound impact of weak infrastructure on resource utilization.

In summary, high-economic-activity regions, with favorable transport conditions and economic advantages, emerge as priority development zones. Conversely, regions with lower economic activity will require the further optimization of the transport infrastructure to unlock their resource development potential. Future policy planning should prioritize allocating resources to support mining development in the economically advanced southeastern regions while enhancing the cross-regional transport networks to gradually improve the economic and transport conditions in the northwestern areas. This will foster coordinated and sustainable resource development across the QXP.

3.3. Multidimensional Constraints of Deposit Size and Ecological Protection

The analysis of the distribution of the ecological reserves and iron deposits on the QXP (Figure 7) highlights the significant spatial constraints imposed by the widespread presence of protected areas on resource development. Moreover, the transport accessibility of deposits outside these protected areas further influences the economic feasibility of their development. Overall, the distribution of protected areas profoundly impacts the spatial pattern of iron ore development, with some high-reserve deposits located within protected areas being inaccessible. In contrast, the distribution and accessibility of deposits outside these areas show a clear trend of decreasing from southeast to northwest.

Approximately 35% of the iron deposits are situated within ecological reserves, where mining is prohibited under the current policy frameworks. These deposits typically exhibit low accessibility scores, with most falling below 0.4, further constraining their economic potential. For instance, some large deposits located in Gansu and the northwest, such as the Zankan iron deposit in Tashkurgan, despite their substantial reserves, are constrained by their locations within protected areas, making them incompatible with the current development conditions. Similarly, several deposits located near Xizang's Ali region and Qinghai's Kekexili, although substantial in reserves, face significant challenges due to their remoteness and strict ecological protection policies.

In contrast, deposits outside protected areas are more widely distributed and generally exhibit significantly higher accessibility. Over 60% of these deposits have accessibility scores greater than 0.7, concentrated primarily in the economically connected and well-developed transport networks of regions such as Northwest Yunnan and Southeast Xizang. From a spatial distribution perspective, high-accessibility deposits outside protected areas are mainly located in the southeastern part of the plateau, particularly in Northwest Yunnan

and Southeast Xizang. These regions are close to densely connected economic hubs like Chengdu, Kunming, and Lhasa, facilitating favorable logistical conditions. For instance, the Sedirang deposit in Gongbujiangda, with an accessibility score of 0.837 and favorable proximity to key cities, is a representative case for prioritized development (Figure 7). Similarly, the Liangzi deposit in Yanxian, with a score of 0.796, also presents significant development potential due to its location on the edge of a protected area and relatively advantageous transport conditions. However, the development of boundary deposits must consider the dynamic potential impacts of changing ecological policies to ensure the sustainability of development plans.

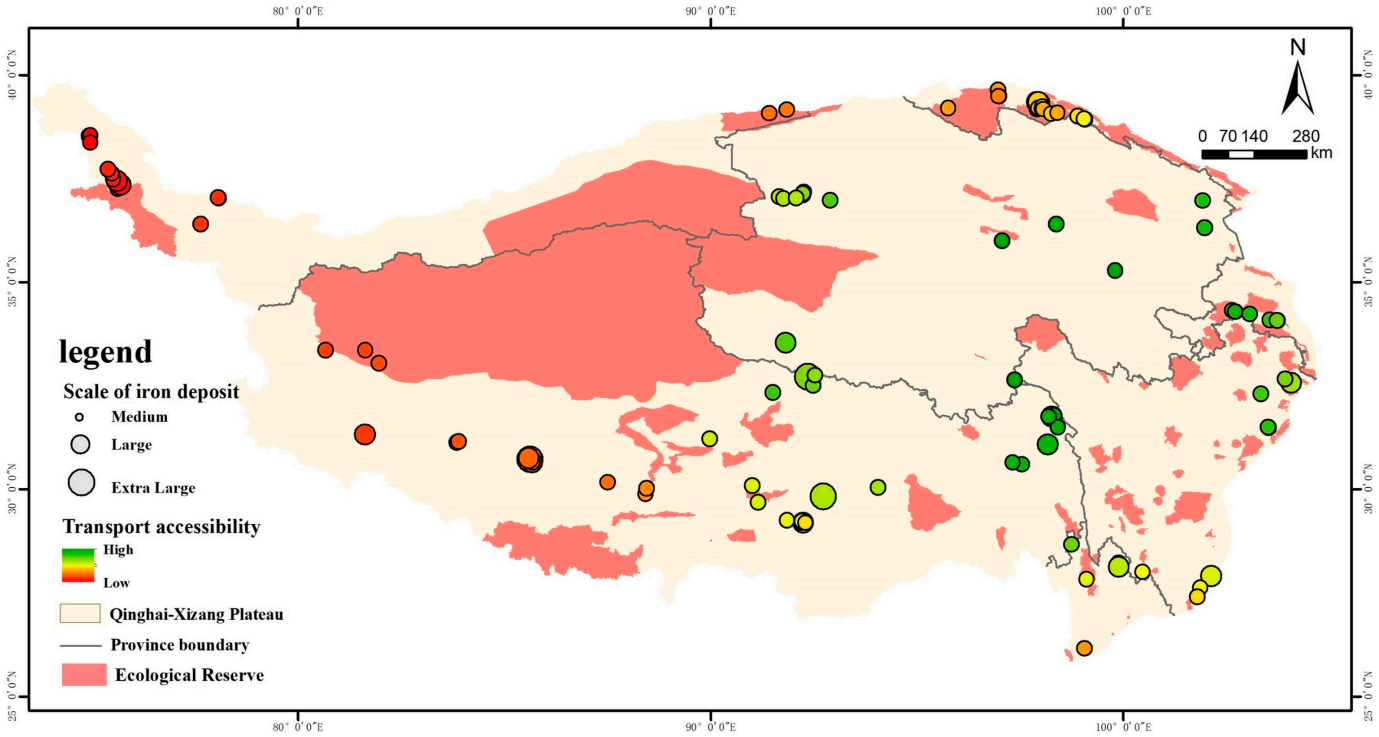

Figure 7. Spatial distribution of iron deposits and ecological reserves on the QXP.

Among the highest-accessibility deposits are those near Changdu, including the Xieba, Jiaduoling, and Kagong deposits. These deposits benefit from their location in a dense transport network with no significant ecological protection zones nearby. These conditions enable more efficient logistics, directly contributing to the higher accessibility scores. Conversely, deposits in the northwestern part of the plateau, characterized by greater distances from urban centers and insufficient transport network coverage, present significant development challenges, representing only 20% of the total number of deposits.

The spatial interaction between ecological reserves and iron deposits reveals regional variations. In the central and western parts of the QXP, the extensive coverage of protected areas markedly limits the spatial availability for resource development. However, in the southeastern region, the coupling effect between protected areas and transport networks is weaker, offering more opportunities to develop iron deposits. This phenomenon is primarily driven by the division created by four significant ecological reserves, the Qiangtang Reserve in Xizang, the Altyn-Tagh National Nature Reserve in Xinjiang, the Kekexili Nature Reserve in Qinghai, and the Central Kunlun Reserve in Xinjiang, which isolate the northwestern and southeastern regions of the plateau. Due to the lack of a direct transport network linking the east from the northwest, most of the transport routes need to bypass Northern Xizang to reach the eastern cities, resulting in significantly lower average distance

accessibility to all iron ore mines located on the western side of the four protected areas than to the eastern level.

This geographical division demonstrates the critical influence of ecological protection zones on both policy and infrastructure development, which indirectly affects the accessibility of deposits located outside these reserves. The disparity reveals the uneven impact of ecological protection policies on regional resource development and underscores the importance of optimizing the transport networks to unlock the regional development potential.

Overall, ecological protection areas exert a dual impact on the spatial distribution and economic viability of iron resource development. The development of deposits within protected areas requires the exploration of ecological compensation mechanisms or innovative development models within permissible policy frameworks. Conversely, the current development planning should prioritize high-accessibility deposits located outside protected areas. In the future, the dynamic optimization of the regional transport infrastructure and ecological policies will further enhance the accessibility and development potential of boundary deposits, thereby achieving a greater balance between resource utilization and ecological protection.

3.4. Future Transportation Optimization and Development

The transportation accessibility of the iron deposits on the QXP exhibits significant regional disparities, with this spatial heterogeneity directly influencing the prioritization of resource development and its economic feasibility. Studies indicate that high-accessibility areas are primarily concentrated in the Northwestern Yunnan and Southeastern Xizang regions, where ore deposits benefit from developed transportation networks and proximity to economic hubs. These areas generally exhibit average accessibility scores greater than 0.7, with over 50% of the regional deposits falling within this category. For example, the Serulang iron deposit in Gongbu Jiangda has an accessibility score of 0.837, and its low logistical costs make it a prime candidate for priority development (Figure 3). This economic feasibility of high-accessibility areas provides a reassuring outlook for the future of resource development. In contrast, the iron deposits in the northwestern region are sparsely distributed, with accessibility scores typically below 0.4, and the logistics costs represent more than 50% of the total development costs. For instance, the development of deposits in the Ali region faces significant economic constraints.

Furthermore, the synergistic effects between transportation accessibility and regional economic development are prominently reflected in their spatial distribution. The spatial overlap between economically developed areas and high-accessibility deposits exceeds 60%, creating a positive feedback loop between transportation networks and economic vibrancy. The Northwestern Yunnan and Southeastern Xizang regions benefit from both complex transportation networks and the enhanced consumption demand and logistics efficiency of neighboring cities, thereby fostering the economic feasibility of resource development. On the other hand, in remote regions of the northwest, the lack of adequate transportation infrastructure results in low accessibility, delayed resource development, and the imbalanced coupling of transportation and economic factors, which further restrict the efficient utilization of regional resources (Figure 6).

At the same time, the widespread distribution of ecological reserves imposes a significant spatial constraint on resource development. Approximately 35% of the iron deposits are located within ecological reserves, where development is strictly regulated by policy, and these deposits generally have accessibility scores below 0.4, indicating poor logistical economic viability. This dual constraint, both policy-driven and economic, makes the development of deposits within these reserves particularly challenging. However, the development potential of high-accessibility deposits outside these reserves is significantly

enhanced, with more than 60% of these deposits located in regions with favorable transportation conditions, thereby presenting a higher priority for development within the current policy framework. For example, the Liangzi iron deposit in Yanxian, despite being located at the edge of a protected area, has an accessibility score of 0.796 and still holds substantial development potential (Figure 7).

Optimizing the transportation infrastructure on the QXP, notably by expanding key transport corridors in the northwestern regions, could significantly improve the development potential of low-accessibility deposits [28], with the accessibility scores potentially increasing by 30% to 50%. Additionally, integrating green mining technologies and ecological compensation mechanisms could allow for limited resource utilization in certain deposits within ecological reserves, achieving a dynamic balance between ecological conservation and resource development.

3.5. Development Suitability Assessment

Transportation accessibility, regional economic development, and ecological protection policies collectively shape the spatial development potential of iron deposits. This analysis reveals that high-accessibility deposits are primarily concentrated in the southeastern regions, including Northwestern Yunnan and Southeastern Xizang, with accessibility scores generally exceeding 0.7, accounting for over 50% of the total deposits. These deposits benefit from their proximity to economic hubs and transportation centers, which provide significant logistical cost advantages, and they are further enhanced by a positive feedback effect from regional economic vibrancy, making them key areas for prioritized development. For example, the Serulang iron deposit in Gongbu Jiangda, with an accessibility score of 0.837, demonstrates strong development potential, further reinforcing the resource development capacity of the southeastern region (Figure 3). Additionally, the Taihe Town iron deposit in Xichang, with an accessibility score of 0.815, is another representative case of a high-priority area for development.

Moderately accessible deposits are primarily located in Eastern Qinghai and Xizang, where the relatively low density of transportation networks still allows for some development potential. The development of these deposits requires dynamic strategies that take into account regional economic development and logistics costs. For example, optimizing the regional road network in Eastern Qinghai could enhance the accessibility scores, thereby significantly reducing the transportation costs and improving the economic feasibility. A typical example is the Liangzi iron deposit in Yanxian, which, with an average distance of 1.8 million meters and an accessibility score of 0.796, indicates considerable development potential, although the scale of development should be adjusted in response to the regional economic conditions and market demand (Figure 3).

Low-accessibility deposits are predominantly concentrated in the northwestern region, accounting for approximately 30% of the total deposits, with accessibility scores generally below 0.3. These deposits, characterized by weak transportation infrastructure and lower economic activity, face limited development potential, with the logistics costs accounting for over 50% of the total development costs. Areas such as Kashgar, Yecheng, and Gaize in Xinjiang, where road networks are sparse and logistics connections are insufficient, exhibit an average transportation distance exceeding 3 million meters. For instance, the Nixiong iron deposit in Cuoqin, Xizang, has an accessibility score of only 0.3, well below the threshold for development suitability. In the short term, the development of these regions is significantly constrained by the transportation infrastructure. Additionally, the distribution of ecological protection zones exacerbates the imbalance in development potential. Approximately 35% of the iron deposits are located within ecological reserves, where development is restricted by policy. Development in these areas must be carried

out within the bounds of policy, potentially utilizing ecological compensation mechanisms or green technology innovations, while the development potential of boundary deposits should be dynamically assessed to account for the potential impact of policy changes (Figure 7).

In the future, optimizing the transportation network on the QXP will be crucial in enhancing the development potential of regional resources. Particularly in the remote northwestern regions, increasing the coverage of key transportation corridors and strengthening regional railway construction could improve the accessibility scores for low-accessibility deposits by 30% to 50%, significantly reducing the development costs and unlocking the resource potential. Moreover, in the southeastern region, further optimization of the transportation infrastructure and the strengthening of the regional logistics network could maximize the resource development efficiency. For deposits within ecological protection areas, development must incorporate green mining technologies and ecological compensation policies to achieve a dynamic balance between resource exploitation and ecological protection.

4. Discussion

4.1. Core Impact of Transportation Accessibility on Iron Ore Development Suitability

The suitability of iron resource development outside the ecological reserves of the QXP is significantly influenced by the spatial gradient of transportation accessibility [48,49]. It is measured using an accessibility score, which considers the transport distances and road network density. The results indicate a strong relationship between this score and the development priority (Figures 3 and 4). The southeastern regions, including Northwestern Yunnan, Southeastern Xizang, and Central Xizang, generally exhibit higher accessibility scores, exceeding 0.7, and account for approximately 50% of the total deposits. This advantage is attributed to the shorter transport distances (<2 million meters) and higher road network density [50]. For example, the Serulang iron deposit in Gongbu Jiangda, with an accessibility score of 0.837, demonstrates superior logistical conditions and significant development potential. In contrast, deposits in the northwestern region are hindered by their weak transportation infrastructure and distant locations from consumption markets [51]. These deposits have accessibility scores below 0.4, representing about 20% of the total deposits. A typical example is the Zankan iron deposit in Tashkurgan, Xinjiang, with an average transport distance exceeding 3.3 million meters and an accessibility score of only 0.048. The resulting high transportation costs significantly constrain its economic feasibility despite its substantial resource reserves.

Further quantitative analysis confirms that transportation accessibility is one of the most significant factors contributing to the overall cost of iron ore development [6]. For deposits in "high-accessibility areas" (with scores > 0.7), reduced logistical costs significantly enhance their economic viability, with these regions strongly coupled with areas of higher economic activity [52]. For instance, the Northwestern Yunnan and Southeastern Xizang deposits exhibit a positive feedback loop between accessibility and economic benefits (Figure 6). In contrast, the development potential of deposits in the northwestern region is constrained by inadequate road network coverage and low logistical efficiency. This spatial disparity creates a significant imbalance in resource development across the QXP, highlighting the importance of transportation accessibility as a core indicator in assessing the iron ore development suitability.

Overall, our findings reveal that the southeastern region of the QXP exhibits relatively high transport accessibility, whereas the northwestern region faces significant accessibility constraints. This result aligns with previous studies that have assessed the overall accessibility of the plateau [7]. However, discrepancies emerge in certain northern areas,

particularly in Gansu. The primary reason for this discrepancy lies in the broader, regional assessments conducted by previous studies, which provide an area-based evaluation of the transport accessibility. In contrast, this study adopts a more refined, point-based evaluation approach that accounts for the specific locations of iron deposits, which are often situated away from major transport networks. To improve the accuracy, we pre-processed the terrain and supplemented the road network, thereby ensuring a more realistic evaluation of the accessibility of the mines to the existing infrastructure. As a result, our methodology delivers a more precise and detailed assessment of the iron deposits' accessibility.

4.2. Constraints of Ecological Protection on Iron Ore Development

Ecological protection imposes significant spatial constraints on iron resource development on the QXP [49]. Approximately 35% of the deposits are located within ecological reserves, where development is not only severely restricted by policy regulations but also faces challenges posed by high altitudes, complex terrain, and other natural conditions, which further elevate the development costs and planning complexity (Figure 7) [53]. The distribution of these protected areas indirectly raises the development priority for deposits outside these zones, especially in high-accessibility areas such as Southeastern Xizang and Central Xizang [27]. However, this strategy is also affected by uncertainties regarding the potential impact of expanding reserve boundaries on neighboring deposits [54]. For example, regarding the Serulang iron deposit in Gongbu Jiangda, despite its rich resource reserves and favorable logistics, with an accessibility score of 0.837, it is still necessary to account for the uncertainties of policy changes and their long-term impacts on project feasibility.

The spatial distribution of the iron deposits relative to the four central ecological reserves, the Qiangtang Nature Reserve in Xizang, the Arjin Mountains National Nature Reserve in Xinjiang, the Kekexili Nature Reserve in Qinghai, and the Central Kunlun Nature Reserve in Xinjiang, exhibits distinct east–west accessibility differences. This pattern reveals the barrier effect of these protected areas regarding the geographic distribution and transportation conditions and highlights the critical impact of ecological reserves on iron ore development [55]. On one hand, these reserves directly prevent the development of iron deposits within their boundaries through stringent policy restrictions [56]. On the other hand, their geographic positioning and extent hinder the optimization of transportation networks, indirectly reducing the accessibility of iron deposits outside the protected areas. This dual limitation effect underscores the profound influence of ecological protection areas on regional resource development and transportation infrastructure planning [57].

The formation of this phenomenon is primarily attributed to the distribution of the four key ecological reserves in the central part of the QXP, which effectively isolates the northwestern region from the southeastern region, forming a natural geographical barrier. Due to the lack of a direct transportation network connecting the northwest with the east, most transport routes must bypass Northern Xizang, passing through Southern Xizang to reach the eastern cities on the QXP. As a result, the iron deposits to the west of these reserves experience significantly higher average transport distances and lower accessibility compared to those in the east [58].

Resolving the conflict between protection and development requires comprehensive policy optimization and regional planning coordination. This crucial need for policy adjustments should be apparent, as the current ecological protection policies could be adjusted through reasonable modifications to the reserve boundaries, with dynamic evaluations and policy exemptions for high-accessibility deposits located at reserve edges, potentially allowing for their development. Such a balanced strategy would enhance resource utilization

and reduce potential disturbances to other ecologically sensitive areas by concentrating on development.

4.3. Relationship Between Deposit Size and Development Priority

The synergistic interaction between the deposit size and transportation accessibility is crucial in determining the development priority of iron deposits on the QXP [42]. The analysis shows that ultra-large and large deposits are typically concentrated in regions with higher accessibility [58]. Due to their large resource reserves and favorable logistical conditions, these deposits hold a significant advantage regarding the development priority [59]. For instance, the Serulang iron deposit, with an accessibility score of 0.837 and an average transport distance of only 1.71 million meters, is located in the core transportation network area of Shannan, showcasing considerable development potential [7]. In contrast, the Taihe Town iron deposit in Xichang, as a typical large deposit, although 227 km from the nearest city, benefits from a well-developed surrounding transportation network, achieving an accessibility score of 0.815 (Figures 3–5). These data indicate that the distribution of ultra-large deposits is primarily driven by the transportation conditions, with the development decisions highly dependent on reducing the logistics costs and supporting regional economies [60].

In contrast, the development potential of medium-sized deposits exhibits more significant spatial variation, necessitating a more adaptable and flexible evaluation of both accessibility and the regional economic conditions. Medium-sized deposits, such as the Liangzi iron deposit in Yanyuan, Northwestern Yunnan, with an average distance of 1.8 million meters and an accessibility score of 0.796, demonstrate significant development potential and relatively favorable logistical conditions. However, in the northwestern QXP, some medium-sized deposits face significant limitations regarding the distance to markets and inadequate transportation network coverage, resulting in accessibility scores below 0.4. These constraints considerably reduce the economic feasibility of their development [46]. This spatial disparity underscores the pivotal role of transportation accessibility in assessing the viability of resource development. It suggests that a more adaptable and flexible development strategy is not just a choice but a necessity for medium-sized deposits [1].

Further analysis indicates that differentiated development strategies should be adopted for varying-sized deposits. For ultra-large and large deposits, due to their high resource reserves and significant economic benefits, policies should prioritize development in high-accessibility regions to maximize the logistical efficiency [8,33]. In contrast, the development strategies for medium-sized deposits should be dynamically adjusted based on the regional market demand, transportation network optimization, and economic feasibility [35]. For example, the medium-sized deposits in the high-accessibility regions of Northwestern Yunnan show considerable development potential. In contrast, some deposits in the northwestern region will rely on future improvements in the transportation infrastructure to enhance their development prospects. This forward-looking approach provides hope and optimism for the future of resource development [1].

Overall, the synergistic relationship between the deposit size and transportation accessibility plays a guiding role in determining development priorities. The concentration of large and ultra-large deposits in high-accessibility areas provides a scientific basis for policy formulation. In contrast, the development of medium-sized deposits must consider the complex dynamic relationship between regional economies and the transportation conditions. These findings provide valuable quantitative data support for iron ore development planning and offer a practical reference for future regional resource development policies.

4.4. Synergistic Effects of Regional Economic Development and Transportation Network Optimization

The synergistic relationship between regional economic development and transportation network optimization exhibits a pronounced bidirectional driving effect on iron resource development on the QXP [47]. Upon correlating the transportation accessibility scores with spatial economic activity data, it is evident that the complex transportation networks and higher economic indices of the Northwestern Yunnan and Southeastern Xizang regions form a significant complementary advantage [61]. Over 50% of the high-accessibility deposits (with scores > 0.7) are concentrated in these regions, where the average transport distance is generally less than 2 million meters, and the economic development level significantly surpasses that of the western QXP. For example, the Serulang iron deposit in Gongbu Jiangda not only benefits from favorable transportation conditions (with an accessibility score of 0.837) but also from its proximity to the economically active region of Shannan, which enhances the logistics efficiency and makes it one of the highest-priority development targets. This phenomenon indicates a high degree of coupling between regional economic activity and transportation network complexity, with both factors mutually reinforcing each other to promote the economic viability of resource development [62].

However, regions such as the northwestern QXP, including Xinjiang's Kashgar area and Xizang's Cuoqin, face constraints due to their sparse transportation networks and lagging economic development [15]. In these regions, the deposits generally have accessibility scores below 0.4, with the average transport distances exceeding 3 million meters. The share of the logistics costs in the total development costs is significantly higher, leading to considerable restrictions on the economic viability of resource development. For instance, despite its substantial resource reserves, the Nixiong iron deposit in Cuoqin faces limited development potential due to its inadequate accessibility. This suggests that transportation limitations and a lack of economic stimulation hinder low-accessibility areas [9].

Transportation network optimization is not just a tool but an imperative to bridge the development gap between regions [46]. Projections indicate that, through future road planning, the accessibility scores of low-accessibility areas could be improved by 30% to 50%, significantly reducing the transportation costs and opening up new economic opportunities for these regions [42]. For example, strengthening the construction of key transportation corridors between the southeastern and northwestern regions will shorten the transport distances for deposits in the northwestern region and enhance the synergistic effects of regional economic growth, improving the overall resource development efficiency. This transportation network optimization strategy alleviates the imbalance in development between regions. It unlocks the resource potential of low-accessibility areas, contributing to the benefits of dual economic and resource development [43].

In summary, the coordinated development of transportation and regional economies is central to achieving balanced resource development on the QXP. With their synergistic advantages in transportation and economics, high-accessibility areas become the core regions for resource development. In contrast, low-accessibility areas rely on transportation network improvements to unlock their potential. This analysis provides quantitative data support for resource development while offering feasible scientific recommendations for regional transportation planning and economic policy formulation. It further emphasizes the pivotal role of transportation network optimization in promoting the coordinated development of regional resources and economies.

4.5. Innovation and Application

The development of mineral deposits in remote areas is often economically unfeasible due to harsh natural conditions and the high costs of transport infrastructure. However,

neglecting these resources has significant consequences, including challenges in sustaining long-term mineral supplies, limiting the expansion of the mineral resource base, and hindering socioeconomic development in resource-rich regions.

This study emphasizes that transportation accessibility alone cannot be the sole determinant of development priorities. A comprehensive evaluation should also consider the geological conditions, socioeconomic factors, ecological environment, and related policies. These multidimensional aspects collectively shape the development potential of mineral resources. By incorporating these factors, future studies can enhance the predictive accuracy and sustainability of development strategies, ensuring that both economic benefits and ecological balance are taken into account.

Therefore, this study introduces a unique multidimensional integrated evaluation model incorporating key factors such as transportation accessibility, deposit sizes, and ecological protection. This model surpasses traditional single-indicator analysis models by providing more comprehensive and precise results. It effectively quantifies resource development's spatial feasibility and economic viability, offering scientific support for regional resource planning under complex natural environments and multiple policy constraints. By assessing the development potential of iron deposits outside the ecological reserves of the QXP, the model successfully reveals the regional imbalances in resource development and provides precise data support for the optimization of development strategies. The study also reveals the important impact of the synergistic effect between transportation and the economy on regional resource development. The Northwestern Yunnan and Southeastern Xizang regions have become the core areas for resource development due to the strong coupling of the transportation network complexity and economic activity [58]. The bidirectional driving effect of transportation accessibility and economic activity significantly promotes the feasibility of iron ore development. In contrast, the northwestern region has become a constrained area for development due to its sparse road networks and economic stagnation [42].

The methodological innovation of this study lies primarily in the construction of a suitability evaluation model that combines multidimensional factors such as transportation accessibility, the resource scale, and ecological protection. Through a quantitative analysis, this study reveals the comprehensive impact of transportation networks, ecological constraints, and the resource scale on development potential. Compared with previous studies, this study conducts a systematic analysis of the QXP, a region with complex geographical and policy contexts, filling the gap in multidimensional integrated evaluation in the field of mineral resource development.

However, the methodology used in this study has certain limitations. For instance, in the evaluation of transportation accessibility, dynamic factors such as road grades and the seasonal traffic capacity were not adequately considered, which may have resulted in the underestimation of the potential of some low-accessibility regions. Furthermore, the model does not fully capture the dynamic impact of market demand changes on mining development decisions, even though the market demand plays a crucial role in the economic benefits of resource development. To address these shortcomings, future studies could integrate dynamic traffic data, high-resolution remote sensing technology, and regional economic forecasting models to improve the accuracy and applicability of the analysis. In particular, the inclusion of dynamic data in high-altitude regions and complex ecological environments will significantly enhance the evaluation of the development potential.

5. Conclusions

This study systematically evaluates the suitability of iron resource development on the QXP through a multidimensional integrated assessment model, focusing on the com-

bined impacts of transportation accessibility, regional economic development levels, and ecological protection policies. The findings reveal significant spatial disparities in the development potential of iron deposits on the QXP. The development potential of the high-accessibility areas in the southeastern part of the plateau is significantly higher than that of the low-accessibility areas in the northwest. In the northwest, iron ore development is often constrained by weak transportation infrastructure. Approximately 35% of the iron deposits on the QXP are located within ecological protection zones and red lines, where development is restricted by policy and accessibility, leading to a relatively low development priority. By analyzing the coupling relationship between transportation accessibility and economic development, this study further reveals the mutually reinforcing effects of regional economic activity and the transportation conditions. Particularly in Northwestern Yunnan and Southeastern Xizang, the geographical advantages of economic centers and transportation hubs maximize the resource development potential. The innovation of this study lies in its first-time emphasis on transportation accessibility, while also considering multiple dimensions such as ecological protection and the regional economy. It constructs a comprehensive model to assess the suitability of iron resource development on the QXP, providing a reference for the rational planning and development of iron deposits in the region.

Future research can progress in multiple directions. Model construction should consider time-varying factors, integrate dynamic variables and policy simulations, and expand the evaluation scale to explore resource–ecology synergies. Regarding resource types and objectives, extending the model to other strategic resources and using multi-objective algorithms can balance economic, ecological, and social aspects. Model validation in fragile regions can be conducted to test its adaptability and provide a resource management paradigm. The "generalized accessibility" model offers innovation but faces challenges in dynamism, resolution, and applicability. Future research, through multidisciplinary and technological efforts, will evolve toward mineral resource assessments to support sustainable utilization and ecological security.

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