Development of a Refined Classification System for Natural Resource Surface Substrates in Arid Regions and Survey Depth: Postprint

Authors: Shuangyuan Li, Xu Zhu, Wang Yugang, Sun Jinjin

Date: 2025-02-27T00:00:00+00:00

Abstract

Surface substrate classification constitutes the foundation for conducting surface substrate survey and monitoring, while also serving as a key to elucidating the synergistic coupling relationship between surface substrate and surface cover layer, thereby facilitating comprehension of the interaction mechanisms between surface substrate and ecological environment from two hierarchical perspectives: surface cover and underground spatial elements. This study selects the Xinjiang Sangong River Basin, a typical inland river basin in arid regions, as the target area. Based on the heterogeneous distribution characteristics of mountain-oasis-desert landscapes in arid regions, and according to the distribution areas, elevation ranges, and primary surface cover types of surface substrates, a three-level classification and zoning system for surface substrates was established. The system is overall partitioned into 4 first-level categories, 17 second-level categories, and 28 third-level categories. According to soil physicochemical properties and vegetation root distribution characteristics, the appropriate survey depth for surface substrates should be 50 cm in the southern mountainous area, 3 m in the central plain area, and less than 10 m in the northern desert area. Furthermore, based on the differentiation characteristics of NPP in vertical zone ecosystems, the rationality of the classification system was validated, reflecting the nurturing and supporting functional relationship of the surface substrate layer to land cover. The research findings provide theoretical and technical support for future natural resources survey, monitoring, and scientific management decision-making in arid regions.

Full Text

Construction of a Refined Classification System and Survey Depth for Natural Resource Ground Substrates in Arid Zones

LI Shuangyuan[1,2,3,4], **XU Zhu**[5], **WANG Yugang**[2,3,4], **SUN Jinjin**[2,3,6]

[1] Key Laboratory of Coupling Process and Effect of Natural Resources Elements, Beijing 100055, China
[2] Key Laboratory of Ecological Safety and Sustainable Development in Arid Land, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, Xinjiang, China
[3] University of Chinese Academy of Sciences, Beijing 100049, China
[4] Fukang Station of Desert Ecology, Chinese Academy of Sciences, Fukang 831505, Xinjiang, China
[5] Bogda Eco-environmental Station, Tianchi Management Committee, Fukang 831500, Xinjiang, China
[6] Field Observation and Research Station of Water Resources and Ecological Effect in Lower Reaches of Tarim River Basin, Ministry of Natural Resources, Urumqi 830057, Xinjiang, China

Abstract

The classification of ground substrates constitutes the foundation for conducting ground substrate surveys and monitoring, while also serving as a key to revealing the synergistic coupling relationship between ground substrates and surface cover layers. This facilitates understanding the interaction mechanisms between ground substrates and the ecological environment from both surface cover and subsurface spatial perspectives. Targeting the Sangong River Basin in Xinjiang—a typical inland river basin in arid regions—this study developed a three-tier classification and zoning system for ground substrates based on the heterogeneous distribution characteristics of mountain-oasis-desert landscapes in arid zones, considering the distribution area, elevation range, and primary surface cover of ground substrates. The overall system comprises four primary categories, 17 secondary categories, and 28 tertiary categories. Based on soil physicochemical properties and vegetation root distribution characteristics, the appropriate survey depth for ground substrates is 50 cm in the southern mountainous area, 3 m in the central plain area, and less than 10 m in the northern desert area. Furthermore, the rationality of the classification system was validated using the differentiation characteristics of Net Primary Productivity (NPP) in vertical zonal ecosystems, demonstrating the nurturing and supporting role of ground substrate layers for land cover. These research findings provide theoretical and technical support for future natural resource surveys, monitoring, and scientific management decision-making in arid regions.

Keywords: ground substrate; classification of ground substrate; survey depth;

arid area; Sangong River Basin

1. Introduction

The concept of ground substrate was explicitly defined in the *Ground Cover Layer Classification Scheme (Trial)* issued by the Ministry of Natural Resources in 2020 (hereinafter referred to as the "Classification Scheme"). Synthesizing definitions and disciplinary foundations from geology, forestry, grassland science, soil science, and hydrology, ground substrate can be summarized as "natural materials formed through natural processes that currently outcrop at the shallow parts of terrestrial surfaces or the bottom of water bodies, and are currently or potentially capable of nurturing and supporting various natural resources such as forests, grasslands, and water bodies." The ground substrate layer extends from the ground surface through the soil to the top of bedrock or the bottom of the vadose zone, serving as a critical link connecting subsurface and aboveground resources. Different ground substrates give rise to different vegetation types, constraining the spatial patterns and evolutionary trends of regional ecosystems. The ground substrate layer acts as the primary carrier for the growth and development of surface cover layers and forms the foundational material supporting various resources including forests, grasslands, and water bodies, playing a crucial role in the formation, evolution, and stability of ecological environments. Nutrient exchange occurs between the ground substrate layer and surface cover layer, as well as with shallow groundwater, while the surface cover layer also exchanges water and heat with shallow groundwater and the atmosphere. These hydrological cycles and energy exchanges among various elements determine the fundamental characteristics of ecosystems. Therefore, ground substrate surveys should emphasize the correspondence between vegetation cover layers and the underlying ground substrates, focusing on the migration and exchange of water, air, and elements in the vadose zone.

Scientific understanding of regional functions and differences in natural resources, revealing the synergistic coupling relationship between ground substrates and surface cover layers, and achieving moderate and effective resource development and utilization to reduce and avoid ecological destruction constitute necessary choices for alleviating the contradiction between resource utilization and environmental protection. The classification of ground substrates must reflect regional ecological service objectives, comprehensively and truthfully represent the basic conditions of ground substrates, and be adapted to local conditions. Rock, gravel, soil, and mud represent different developmental stages of ground substrate evolution and are material foundations that sustain Earth ecosystem functions and human survival. The Classification Scheme divides ground substrates into four primary categories—rock, gravel, soil, and mud—with 12 secondary categories. However, in practical application, the scheme lacks clear refinement protocols for tertiary classification. While several scholars have explored ground substrate survey directions in different typical regions, these studies have primarily focused on southern China and black soil regions, with limited discussion on refined classification systems and applications for ground substrates in arid zones. Currently, no comprehensive evaluation index system exists for ground substrate quality in arid regions, and challenges remain in expressing survey results for ground substrate layers.

Consequently, this study targeted the Sangong River Basin as a case study area, collecting and organizing regional land use data, remote sensing imagery, soil profile data, vegetation cover types, and hydrogeological information. Building upon the primary and secondary categories in the Classification Scheme, we investigated ground substrate types, vertical zoning, vegetation distribution, and other material components attached to or within the main substrate components to develop a refined tertiary classification scheme appropriate for the region. From the perspectives of classification standards, representative regional ranges, and correspondence with vegetation cover layers, we established a classification index system for ground substrates in arid regions. Through field surveys and experimental measurements, we validated the feasibility and accuracy of the regional ground substrate classification system, aiming to provide a referenceable approach for refined classification of ground substrates at different spatial scales.

2. Study Area and Methods

2.1 Study Area Overview The Sangong River Basin is located in the eastern central section of the northern foothills of the Tianshan Mountains, on the southern margin of the Junggar Basin (87°46 ~88°44 E, 43°45 ~45°30 N), and features a typical temperate continental arid climate [Figure 1: see original paper]. The region exhibits dramatic elevation differences ranging from 437 m to 5,152 m, with terrain sloping from high in the south to low in the north. Adjacent to the Gurbantünggüt Desert in the north, temperatures gradually increase from south to north. Annual precipitation is approximately 200 mm, concentrated between May and September, accounting for about 70% of the total annual precipitation. Water resources are relatively abundant, primarily dependent on meltwater from alpine glaciers and snow, as well as atmospheric precipitation. Groundwater consists mainly of Quaternary loose rock pore water, with profile distribution controlled by formation lithology and regional geomorphology.

The study area exhibits typical vertical zonal geomorphological characteristics, primarily divided into three units: southern mountainous area, central plain area, and northern desert area. From south to north, these can be further classified into five geomorphological types: alpine meadow zone, mid-mountain forest zone, low mountain and hill zone, alluvial-proluvial plain, and aeolian desert. The geological structure is relatively complex in the southern mountainous area and relatively simple in the northern plain area. Within the elevation range of this study, areas above 3,500 m are covered by alpine ice and snow, with modern glaciers developing. Since vegetation is essentially absent from these areas, they are not separately shown in the schematic diagram of geomorphological zoning and surface cover relationships. Impermeable layers exist in the study area, mainly distributed at the edge of the alluvial-proluvial fan and the upper part of the alluvial-proluvial plain in the central plain area, with lithologies consisting of interbedded fine sand, sub-sand, sub-clay, and clay. Due to the presence of these impermeable layers, groundwater overflow zones form at the fan margins and upper alluvial-proluvial plain, with no hydraulic connection between the upper and lower aquifers, requiring separate consideration in classification.

2.2 Data Sources **Soil Data:** Considering the distribution characteristics of land use and irrigation methods, we selected soils with different soil types, land use types, and irrigation methods in the central plain oasis area of the study area. Using different groundwater depths as grouping criteria, we paired farmland plots with adjacent natural background desert plots, establishing a total of four sampling sites (S1&S2, S3&S4). Soil samples were collected at 20 cm intervals until reaching the groundwater table, yielding 120 profile samples. The collected soil samples were air-dried in a ventilated indoor environment, fully ground, and passed through a 2 mm sieve for reserve. Following the testing methods in *Soil Agricultural Chemical Analysis* [21], we determined the composition of various soil ions and described the vertical changes in soluble salt ions and salt content by layer. Land use, hydrogeological, and plant root data for the Sangong River Basin were obtained from historical survey data from the Fukang Desert Ecosystem National Field Observation and Research Station.

Meteorological and Remote Sensing Data: Meteorological data included temperature and precipitation, while remote sensing data comprised solar radiation, NDVI, and vegetation cover type data . All data underwent preprocessing including reprojection, mosaicking, clipping, unit conversion, and resampling for model operation and data analysis. This study used Excel for data organization, SPSS 26 for statistical analysis, ArcGIS 10.8 for spatial analysis, and Origin Pro 2024 for graphing and visualization.

2.3 Research Methods **Net Primary Productivity Model:** Net Primary Productivity (NPP) refers to the amount of organic matter accumulated by vegetation per unit area per unit time, driven by both climatic factors and human activities. The NPP model integrates multiple environmental data to simulate regional vegetation net primary productivity, demonstrating good accuracy and thus being widely applied in NPP research. The NPP data used in this paper were calculated using the model developed by Zhu Wenquan et al. [22], with detailed formulas provided in the literature. Meteorological and remote sensing data used in the model are listed in Table 2.

Ground Substrate Zoning and Classification: From the perspective of the relationship between ground substrates and surface cover layers, we divided the study area into southern mountainous region, central plain region, and northern desert region based on geomorphological types [Figure 2: see original paper]. We then developed an appropriate ground substrate classification system for each zone. In the southern mountainous region, rock substrate classification was based on genetic type and rock hardness. Gravel substrate classification was based on geomorphological and genetic types, reflecting the influence of terrain and landforms on ground substrate development processes. Soil substrate classification was relatively more detailed, divided according to soil formation processes and properties into 9 secondary categories and 16 tertiary categories. Additionally, based on regional characteristics, an "other"category (impermeable layer clay) was added to the primary classification.

Validation of Classification System Rationality and Survey Depth: Net Primary Productivity (NPP) is an important indicator for quantifying vegetation carbon sequestration capacity and oasis ecological effects, with its spatial and temporal variations reflecting vegetation responses to ground substrate changes. Therefore, identifying the spatial and temporal patterns of NPP in the Sangong River Basin can validate the correspondence between ground substrate layers and vegetation cover layers in this classification system, indirectly demonstrating the rationality of the classification system in regional ground substrate survey applications.

3. Results

3.1 Ground Substrate Classification Scheme

3.1.1 Southern Mountainous Region In the southern mountainous region, with elevation ranges greater than 700 m (excluding the alpine ice and snow zone above 3,500 m with virtually no vegetation), the classification includes four primary categories, 10 secondary categories, and 16 tertiary categories. Rock substrate is classified into 4 secondary categories and 4 tertiary categories based on genetic type and rock hardness. Harder igneous and metamorphic rocks are distributed in the alpine and mid-mountain zones above 1,600 m, constituting high- and medium-altitude rock areas. Hard sedimentary rocks and relatively soft sedimentary rocks are distributed in the mid-mountain forest zone at approximately 1,600–2,700 m, characterized by pure forests of Schrenk' s spruce with understory shrubs and herbaceous plants. Relatively hard sedimentary rocks and soft sedimentary rocks are distributed in the low mountain and hill zone at approximately 700–1,600 m, with steppe vegetation dominated by Artemisia and grasses.

Gravel substrate includes two secondary categories: boulders and cobbles. Tertiary categories comprise alpine glacial boulders distributed in the alpine ice and snow zone, and low mountain hill boulders distributed in the low mountain and hill zone.

Soil substrate is classified into four secondary categories and 10 tertiary categories based on soil formation processes and properties [Figure 3: see original paper]. Alpine desert soil is distributed in the alpine ice and snow zone above 3,500 m with sparse vegetation. Alpine meadow soil is distributed in the alpine zone at 3,000–3,500 m, supporting alpine meadows. Subalpine meadow soil is distributed in the subalpine zone at 2,700–3,000 m. Mountain gray-cinnamon soil and chernozem are distributed in the mid-mountain forest zone at 1,600–2,700 m, supporting spruce forests and mesophytic grasslands. Chestnut soil and brown soil are distributed in the low mountain and hill zone at 700–1,600 m, forming mountain steppe with 20–40% vegetation cover.

3.1.2 Central Plain Region The central plain region, with elevations of 470–700 m, includes two primary geomorphological types: alluvial-proluvial fan and alluvial-proluvial plain. Rock substrate is primarily sedimentary rock, classified as extremely soft sedimentary rock distributed in the alluvial-proluvial fan area. Gravel substrate includes boulders, cobbles, and pebbles, distributed in the gobi gravel zone and alluvial-proluvial fan, with fine gravel in the upper alluvial-proluvial plain. Vegetation consists of sparse xerophytic and super-xerophytic plants with low coverage.

Soil substrate is classified into three secondary categories (desert soil, semi-hydromorphic soil, and anthropogenic soil) and nine tertiary categories [Figure 4: see original paper]. Gray desert soil and gray-brown desert soil are distributed in the gobi gravel zone at the mountain front. Meadow soil and irrigation-silt soil are distributed in the lower fan margin and along rivers, supporting farmland and vegetation such as reeds and Achnatherum splendens. Meadow solonchak and desert solonchak are distributed in the fan margin and alluvial-proluvial plain, with vegetation dominated by artificial vegetation and Tamarix, Phragmites, and Achnatherum. Due to the presence of impermeable layers with low permeability coefficients and good plasticity, an additional "other" category (impermeable layer clay) was included.

3.1.3 Northern Desert Region The northern desert region, at approximately 430–470 m elevation, is dominated by soil substrate. Based on common characteristics of soil formation processes and properties, the secondary category is primarily initial developmental soil, with the tertiary category classified as aeolian sand. The corresponding vegetation includes Haloxylon ammodendron, Haloxylon persicum, Reaumuria soongorica, Suaeda spp., and Alhagi sparsifolia, accompanied by some perennial herbaceous plants. Vegetation cover is approximately 20%, with relatively abundant ephemeral plant species .

3.1.4 Correspondence Between Ground Substrate Layer and Vegetation Cover Layer The spatial distribution of mean NPP values in the Sangong River Basin shows significant spatial heterogeneity [Figure 5: see original paper]. High NPP values are primarily distributed in the mid-mountain forest zone of the southern mountainous area (508.62 g $C \cdot m^{-2}$) and the oasis area of the central plain alluvial-proluvial fan (334.2 g $C \cdot m^{-2}$), while low values are mainly in the northern desert area (77.64 g $C \cdot m^{-2}$) and alpine meadow zone of the southern mountains (121.21 g $C \cdot m^{-2}$). This spatial distribution aligns with the vegetation cover characteristics corresponding to different ground substrate types in various geomorphological zones, demonstrating the rationality of the classification system in regional ground substrate survey applications.

3.2 Determination of Survey Depth

3.2.1 Southern Mountainous Region The southern mountainous region contains bedrock weathering crusts and residual slope deposits. Survey depth primarily considers the functional requirements of supporting vegetation communities, generally determined by the depth of underground vegetation root systems. Field investigations revealed that in the alpine meadow zone, herbaceous vegetation roots are concentrated in the 20–30 cm depth range. In the mid-mountain forest zone, Schrenk' s spruce and understory grassland roots are concentrated at 20–50 cm depth with high vegetation coverage. In the low mountain and hill zone, vegetation roots are mainly distributed in the 20–30 cm depth range with 20–40% coverage [Figure 6: see original paper]. Overall, plant roots across different elevations in the southern mountainous region are concentrated within 50 cm depth.

3.2.2 Central Plain Region Soil salinity profiles in farmland show that total salt content and most ion concentrations peak at the surface and decrease with depth. In the 0–1.2 m section, salt content decreases with depth, while in the 1.2–6.4 m section, it fluctuates within a relatively low range [Figure 7: see original paper]. In natural desert profiles, total salt content peaks in the 0–0.3 m layer and decreases with depth, stabilizing below 1.8 m [Figure 8: see original paper]. These patterns indicate that soil water-salt movement causing surface salt accumulation primarily occurs above 1.8–2.2 m depth. Below this depth, the impact on surface environment, vegetation roots, and human activities weakens. Therefore, a survey depth of 2.2 m meets the requirements for ground substrate investigation in the central plain oasis area.

3.2.3 Northern Desert Region The northern desert region features fixed and semi-fixed dunes with vegetation cover gradually decreasing from the southern margin to the interior. The main vegetation types are Haloxylon ammodendron, Tamarix ramosissima, and Reaumuria soongorica. Root distribution analysis shows that H. ammodendron roots are primarily distributed in the 0–10 m soil layer, with 94.29% of total root surface area in this range [Figure 10: see original paper]. T. ramosissima is a deep-rooted species with roots distributed at 0.5–3.1 m depth, while R. soongorica is a shallow-rooted species with roots at 0–0.8 m depth [Figure 9: see original paper]. Considering practical survey feasibility, a survey depth of 10 m effectively reflects the vegetation community support function and meets ground substrate survey requirements in the northern desert region.

4. Discussion

Ground substrate surveys emphasize different aspects in different regions, and depth determination should be based on regional ecological functional requirements, comprehensively considering the lower depth limit that can influence ecosystems, without setting uniform standards. Previous research suggests that, except in low-lying areas, a survey depth encompassing surface attachments, soil cultivation layers, and plant root depths generally meets requirements. This study focused on vegetation community greening and ecological protection, primarily investigating ground substrate classification based on surface vegetation cover characteristics. Therefore, actual surveys must also consider factors with significant impacts on vegetation.

In the southern mountainous region, bedrock weathering crusts and residual slope deposits are present. Soil nutrients are key environmental factors limiting the growth of Schrenk's spruce, the dominant species in the mid-mountain forest zone. The shallow root system of this species primarily utilizes surface soil water from atmospheric precipitation or snowmelt infiltration rather than groundwater recharge. Combined with actual root distribution patterns in key constraint layers, a survey depth of 50 cm is appropriate for the southern mountainous region.

In the central plain region, soil parent materials are primarily Quaternary alluvial-proluvial or aeolian deposits. Groundwater depth in oasis areas is substantial, with mild soil salinization. Since crop roots are concentrated in surface soil (the cultivation layer), the survey depth should reflect the depth of water-salt movement causing surface salt accumulation. Profile analysis indicates that a depth of 2.2 m is suitable for both farmland and natural desert areas in the central plain oasis region.

In the northern desert region, soil water is the direct source of water for vegetation growth, closely linking atmospheric and groundwater systems. Sparse natural precipitation alone cannot meet the normal growth requirements of some plants, making groundwater an important component of plant water use. Due to low rainfall, minimal surface runoff, and good permeability of aeolian soils, soil water originates primarily from atmospheric precipitation and groundwater. Considering the root distribution of dominant species H. ammodendron and practical survey feasibility, a survey depth of 10 m is appropriate for the northern desert region.

5. Conclusions

Based on the scientific connotation of ground substrates and existing research, combined with vegetation characteristics and relevant soil surveys in arid regions, this study draws the following conclusions:

1) A new approach for refined classification and zoning of ground substrates in arid regions was proposed. From the perspective of the close relationship

between natural resource ground substrates and surface cover, combined with geomorphological types, representative regional ranges, and vegetation cover correspondence, the study area was divided into southern mountainous region (including alpine meadow, mid-mountain forest, and low mountain hills), central plain region (alluvial-proluvial fan and alluvial-proluvial plain), and northern desert region, with a regional ground substrate classification system constructed for each zone.

2) The refined classification of ground substrates in the Sangong River Basin was completed. Rock substrate was classified into 4 secondary and 4 tertiary categories based on genetic type and rock hardness. Gravel substrate was classified into 4 secondary and 5 tertiary categories based on genetic type and geomorphology. Soil substrate was classified into 9 secondary and 16 tertiary categories based on soil formation processes and properties. Additionally, an "other" category (impermeable layer clay) was added to the primary classification according to regional characteristics.

3) Based on typical soil profile salt ion content, groundwater, and vegetation root distribution characteristics, the appropriate survey depth for ground substrates is 50 cm in the southern mountainous region, 3 m in the central plain oasis area (based on water-salt movement causing surface salt accumulation), and 10 m in the northern desert region (based on vegetation root depth). These depths effectively reflect the functional role of ground substrates in supporting vegetation communities and meet survey requirements.

References

[1] Ministry of Natural Resources. Notice of the General Office of the Ministry of Natural Resources Printing and Distributing the *Ground Cover Layer Classification Scheme (Trial)* [EB/OL]. 2020, http://gi.mnr.gov.cn/202012/t20201222_{2596025}.html.

[2] Yin Zhiqiang, Chen Ziran, Li Xia, et al. Connotation, layering, mapping and supporting objectives of the integrated survey of ground substrates[J]. Hydrogeology & Engineering Geology, 2023, 50(1): 144-151.

[3] Sun Xiyong, Xu Wei, Wang Mingjian. Investigative study on stratification and classification of surface substrates layers[J]. China Land, 2022(7): 34-36.

[4] Zhu Yongguan, Li Gang, Zhang Ganlin, et al. Soil security: From Earth' s critical zone to ecosystem services[J]. Acta Geographica Sinca, 2015, 70(12): 1859-1869.

[5] Yin Zhiqiang, Qin Xiaoguang, Zhang Shuji, et al. Preliminary study on classification and investigation of surface substrate[J]. Hydrogeology and Engineering Geology, 2020, 47(6): 8-14.

[6] Ge Liangsheng, Hou Hongxing, Xia Rui. Construction of technical system for ground substrate survey of natural resources[J]. Geomatics World, 2022, 29(5):

20-27.

[7] Ai Xiaojun, Chen Zhansheng, Geng Guoshuai, et al. Distribution patterns and influencing factors of effective soil layers in the surface matrix of black soil in Liaoyang-dandong area—Taking Fengcheng city as an example[J]. Journal of Hebei Agricultural Sciences, 2023, 27(3): 54-59, 65.

[8] Huo Dong, Chen Zhansheng, Ai Xiaojun, et al. Application of remote sensing interpretation in surface substrate investigation of black soil in Liaoyang-dandong region: Taking Kuandian Manchu Autonomous County as an example[J]. Agriculture and Technology, 2023, 43(15): 115-119.

[9] Liu Hongbo, Kong Fanpeng, Zhao Jian, et al. Exploration and experiment of surface substrate investigation technique: A case study of black soil investigation in Baoqing County, Heilongjiang Province[J]. Geomatics World, 2022, 29(6): 1-5.

[10] Sun Yonggang, Zhang Chuang, Shang Xiaoyu, et al. Exploration and study on physiochemical properties of different ground substrate types: Taking the Saihanba demonstration area in Hebei Province as an example[J]. Resource Information and Engineering, 2023, 38(2): 13-16.

[11] Chen Bingming, Zhao Shanchao, Sun Fenghua, et al. Impacts of climate change and human activities on the NPP of vertical natural belts in arid zones[J]. Chinese Journal of Ecology, 2023, 42(6): 1474-1483.

[12] Hao Xinyi, Zhang Zhe, Zheng Hao, et al. Dynamic change of vegetation cover in the economic zone of the northern slopes of Tianshan Mountains[J]. China Environmental Science, 2024, 44(2): 1020-1031.

[13] Wang Genxu, Cheng Guodong. The spatial pattern and influence caused by water resources in arid desert oases[J]. Acta Ecologica Sinica, 2000, 20(3): 363-368.

[14] Li Yanzhong, Luo Geping, Xu Wenqiang, et al. Forest development and their relationships with climatic and soil in the mid-mountain area of Sangong River watershed, northern slope of Tianshan Mountains[J]. Journal of Mountain Science, 2011, 29(1): 33-42.

[15] Lu Rukun. The Analysis Method of Soil Agricultural Chemistry[M]. Beijing: China Agricultural Science and Technology Press, 2000.

[16] He Qinghua, Xie Yun. Research on the climatological calculation method of solar radiation[J]. Journal of Natural Resources, 2010, 25(2): 308-319.

[17] Luan Haijun, Xing Chenshuo, Zhang Rongkai, et al. Analysis of fractal characteristics of NDVI scale conversion based on Chen NDVI model[J]. Remote Sensing Information, 2022, 37(3): 12-20.

[18] Zhu Wenquan, Pan Yaozhong, Long Zhonghua, et al. Estimating net primary productivity of terrestrial vegetation based on GIS and RS: A case study in Inner Mongolia, China[J]. Journal of Remote Sensing, 2005, 9(3): 300-307.

[19] Yang H, Zhong X, Deng S, et al. Assessment of the impact of LUCC on NPP and its influencing factors in the Yangtze River basin, China[J]. Catena, 2021, 206: 105542.

[20] Hu C, Zhang L, Wu Q, et al. Response of LUCC on runoff generation process in Middle Yellow River Basin: The Gushanchuan Basin[J]. Water, 2020, 12(5): 1237.

[21] Yin Xiaojun, Zhu Honghui, Gao Jerry, et al. Effects of climate change and human activities on net primary productivity in the Northern Slope of Tianshan, Xinjiang, China[J]. Transactions of the Chinese Society of Agricultural Engineering, 2020, 36(20): 195-202.

[22] Zhu Wenquan, Chen Yunhao, Xu Dan, et al. Advances in terrestrial net primary productivity (NPP) estimation models[J]. Chinese Journal of Ecology, 2005, 24(3): 296-300.

[23] Song Xinni, Li Lu, Chang Yapeng, et al. Stoichiometric characteristics of nitrogen and phosphorus in leaves and soils of Picea schrenkiana spruce forest on the northern slope of the Tianshan Mountains[J]. Journal of Northwest A & F University (Natural Science Edition), 2020, 48(9): 97-104.

[24] Long Weiyi, Shi Jianfei, Li Shuangyuan, et al. Evaluation of multimodel inversion effects on soil salinity in oasis basin[J]. Arid Zone Research, 2024, 41(7): 1120-1130.

[25] Sun Fangqiang, Yin Lihe, Ma Hongyun, et al. Identification of soil water migration and recharge sources in the southern marginal zone of the Junggar Basin, China[J]. Arid Zone Research, 2017, 34(6): 1271-1277.

[26] Tian Shengchun, Zhao Shanchao, Zheng Xinjun, et al. Water source of spruce (Picea schrenkiana) at different altitudes in the Tianshan Mountains during the growing season[J]. Arid Zone Research, 2023, 40(3): 436-444.

[27] Dong Xue, Li Yonghua, Xin Zhiming, et al. Variation in Nitraria tangutorum leaf traits and leaf δ^{13}C and δ^{15}N content along precipitation gradient[J]. Acta Ecologica Sinica, 2019, 39(10): 3700-3709.

[28] Sun Fangqiang, Yin Lihe, Wang Xiaoyong, et al. Determination of vertical infiltration recharge of groundwater in the thick unsaturated zone of Sangong River Basin, Xinjiang[J]. Geology in China, 2017, 44(5): 913-923.

[29] Dai Yue, Zheng Xinjun, Tang Lisong, et al. Dynamics of water usage in Haloxylon ammodendron in the southern edge of the Gurbantünggüt Desert[J]. Chinese Journal of Plant Ecology, 2014, 38(11): 1214-1225.

[30] Xu Guiqing, Li Yan. Roots distribution of three desert shrubs and their response to precipitation under co-occurring conditions[J]. Acta Ecologica Sinica, 2009, 29(1): 130-137.

[31] Luo M, Meng F, Sa C, et al. Response of vegetation phenology to soil moisture dynamics in the Mongolian Plateau[J]. Catena, 2021, 206: 105505.

[32] Zeng J, Li Z, Chen Q, et al. Evaluation of remotely sensed and re-analysis soil moisture products over the Tibetan Plateau using in-situ observations[J]. Remote Sensing of Environment, 2015, 163: 91-110.

[33] Zhao Wenzhi, Liu Hu. Recent advances in desert vegetation response to groundwater table changes[J]. Acta Ecologica Sinica, 2006, 26(8): 2702-2708.

[34] Xu Hailiang, Song Yudong, Wang Qiang, et al. The effect of groundwater level on vegetation in the middle and lower reaches of the Tarim River, Xinjiang, China[J]. Chinese Journal of Plant Ecology, 2004, 28(3): 400-405.