Climate Change in Arid Regions and Its Impacts on Mountain Forest Ecosystem Stability and Hydrological Processes: A Review (Postprint)

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Abstract

In arid regions, water constitutes the fundamental element for oasis formation. Alpine regions in arid areas serve as the water source that sustains the existence of oases in northwestern arid regions, supports local sustainable economic development, and maintains ecological stability. Mountain forest ecosystems play a crucial role in water conservation and are referred to as "green reservoirs." Climate change will alter the structure, composition, and water cycle of mountain ecosystems, exacerbate water scarcity, and threaten oasis security in arid regions. This paper reviews and synthesizes research progress on climate change in arid regions and its impacts on the stability and hydrological processes of mountain forest ecosystems in these areas, identifies existing problems in current research, and proposes that future studies in arid region mountains should evaluate climate change trends at spatial resolutions finer than 1 km. Comprehensive research should be conducted from multi-scale, multi-interface, multi-disciplinary, and multi-method perspectives on the impacts of climate change on the stability and hydrological processes of mountain forest ecosystems in arid regions. This will promote the development of mountain ecology in arid regions, provide a theoretical foundation for management departments in arid regions to adapt to and mitigate climate change, scientifically formulate water resource management plans under climate change conditions, and achieve effective water resource management, thereby promoting environmental and socioeconomic sustainability in arid regions under climate change conditions.

Full Text

Advances in Climate Change and Its Impact on the Stability of Mountain Forest Ecosystems and Hydrological Processes in Arid Regions

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Abstract

Water is the fundamental element for oasis formation in arid regions. Alpine mountains in northwest China' s arid areas serve as critical water source zones that sustain oasis existence, support sustained local economic development, and maintain ecological environmental stability. Mountain forest ecosystems play a vital water conservation function, earning them the designation of "green reservoirs." Climate change will alter mountain ecosystem structure and composition, modify terrestrial water cycle elements, exacerbate water resource shortages, and threaten oasis security in arid regions. This paper reviews research progress on climate change and its impacts on the stability and hydrological processes of mountain forest ecosystems in arid regions, identifies existing problems in current research, and proposes future directions. Specifically, we argue that climate change trends in arid mountain regions must be assessed at spatial resolutions finer than 1 km. Comprehensive studies should be conducted from multi-scale, multi-interface, multi-disciplinary, and multi-method perspectives to investigate climate change impacts on mountain forest ecosystem stability and hydrological processes. This approach will promote the development of mountain ecology in arid regions, provide a theoretical foundation for management departments to adapt to and mitigate climate change, enable scientifically sound water resource management planning under changing climate conditions, and facilitate effective water resource management to promote sustainable environmental and socioeconomic development in arid regions under climate change.

Keywords: climate change; ecosystem stability; forest ecohydrological processes; arid region alpine mountains

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1. Climate Change Research in Northwest Arid Regions

Temperature and precipitation are the primary climatic drivers of ecosystem processes from regional to global scales. Research has revealed increasing trends in both temperature and precipitation in northwest China' s arid region. Analysis of 60 meteorological stations showed that temperatures in mountainous, oasis, and desert areas increased by 0.34 °C · (10a)^-1, 0.36 °C · (10a)^-1, and 0.39 °C · (10a)^-1, respectively, while precipitation increased by 10.15 mm · (10a)^-1, 6.29 mm · (10a)^-1, and 0.87 mm · (10a)^-1, respectively—rates significantly exceeding the global average. Studies of the Qilian Mountains specifically show that since 1961, the northern slope has experienced warming and wetting trends with annual mean temperature and precipitation increasing at rates of 0.033 °C · a^-1 and 0.57 mm · a^-1, respectively. In the central Qilian Mountains, the average annual temperature has risen at 0.39 °C · (10a)^-1 over the past 60 years, with total precipitation on rainy days increasing at 13.86 mm · (10a)^-1. Both observations and simulations demonstrate intensified warming in arid regions over the past century, with high-altitude mountain ecosystems and tundra zones responding more sensitively and rapidly to global warming. However, these studies primarily reflect climate change trends at coarse spatial resolutions, whereas managers require higher-resolution climate change research products to establish and guide climate adaptation strategies.

2. Climate Change Impacts on Mountain Forest Ecosystem Stability

Rising temperatures and altered spatiotemporal precipitation distribution represent the most significant characteristics of climate change. These changes have substantially impacted terrestrial ecosystem stability, manifested through phenological shifts and extended growing seasons, altered tree growth patterns, upward migration of alpine treelines, and tree mortality. The continuous changes in forest composition, structure, and function largely depend on how individual forest populations respond to changing environmental drivers and disturbance regimes. Ecosystem stability is defined as a community' s capacity to resist change and can be quantitatively expressed as the ratio between the mean and variability of selected characteristic indicators. Climate change impacts on ecosystem temporal stability can be summarized through resistance and resilience metrics, which primarily consider synchronous and lagged effects of climate change on ecosystems.

Recent studies have advanced our understanding of these dynamics. Research using tree-ring width data and satellite imagery networks compiled absolute annual indicators of forest growth and productivity for 21 forest types across Mediterranean, temperate, and continental biomes in Spain, revealing that forest structural diversity positively influences stability while population density has negative effects. Precipitation variability and slope primarily affect stability indirectly through their influence on tree species richness. At the global scale, studies of evergreen broadleaf forest communities found that resistance and resilience are mainly controlled by temperature and radiation. In China' s subtropical forests, species richness and stand structure diversity enhance stability, while population density reduces it. However, for alpine mountain forest ecosystems in arid regions, mechanisms linking climate change to forest structure and spatial pattern changes remain unclear. Questions persist regarding how climate-biodiversity relationships translate into complex forest structural patterns and how climate change affects forest ecosystem stability. Clarifying these mechanisms is essential for providing theoretical foundations for climate change adaptation and selecting appropriate mitigation strategies.

3. Climate Change Impacts on Ecosystem Hydrological Processes

Changes in terrestrial ecosystem stability inevitably alter water balance and plant water processes, modify land surface water cycle elements such as soil moisture and evapotranspiration, accelerate ecosystem water cycling, and consequently affect water yields in forested areas. Forest hydrological processes primarily include canopy interception, throughfall, evapotranspiration, understory and soil water storage, and runoff generation. This section focuses on four key aspects: soil moisture dynamics, evapotranspiration processes, root water uptake, and coupled modeling studies.

3.1 Climate Change Impacts on Soil Moisture Soil moisture is the primary link connecting climate, vegetation, and hydrological processes. Climate change, particularly precipitation variability, dominates soil moisture dynamics, while plant diversity promotes soil moisture heterogeneity. Precipitation changes and vegetation cover are key factors controlling soil moisture spatiotemporal variation. In arid alpine mountain forest ecosystems, however, the interactions between climate and soil moisture at plot, slope, and watershed scales remain poorly understood. The driving mechanisms of soil moisture spatiotemporal variability lack comprehensive quantitative results. Since many hydrological processes are nonlinear functions of soil moisture, in-depth understanding of soil moisture dynamics is essential for representing these processes at larger scales. Recent studies have employed wavelet analysis to examine soil moisture dynamics across grassland, forest, and invasive species zones, revealing coherence between precipitation variability and soil moisture fluctuations. A novel experimental and numerical framework investigated how tree architectural traits affect stemflow and soil water dynamics on Scottish slopes. However, for arid alpine mountain forests, integrated quantitative results on climate-soil moisture interactions across scales are still lacking, hindering effective water resource management and climate impact assessment.

3.2 Climate Change Impacts on Evapotranspiration Processes Climate change has extended vegetation growing seasons and altered physiology and phenology, thereby modifying evapotranspiration (ET) processes. Global ET has increased at 0.88 mm·a^-1 from 1982-2011, while precipitation increased at 0.66 mm·a^-1. However, excessive warming may accelerate soil water evaporation, creating drought trends. In arid regions, potential ET shows increasing trends in 70.6% of areas in winter, 64.7% in spring, 70.6% in summer, 76.5% in autumn, and 70.0% annually. Process-based soil water models reveal that despite increased winter and spring precipitation, elevated ET can reduce late spring and summer soil moisture. Forest cover changes significantly impact ET, with studies showing that a 68.0% increase in forest coverage raised average ET by 50% in certain catchments. For arid alpine mountain forest ecosystems, however, the mechanisms by which climate and stability changes alter ET processes remain unclear. Understanding these mechanisms is crucial for effective water resource management and improving climate impact assessment quality.

3.3 Root Water Uptake Studies Root water uptake plays a crucial role in soil moisture spatiotemporal evolution. Plants absorb soil water through roots, which then enters the atmosphere through transpiration and soil evaporation, creating a continuous soil-plant-atmosphere system. Understanding root water uptake patterns is fundamental for comprehending soil moisture variability drivers and climate change impacts on vegetation hydrological processes. Studies using ground-penetrating radar and root coring have investigated root distribution patterns in Mongolian pine plantations of different ages, recommending that stand density should be determined based on root area to avoid degradation or mortality from water competition. Neural network and multiple regression models have been developed to predict sap flow in Qinghai spruce, highlighting the importance of time-lag effects and soil moisture conditions. Recent advances incorporate root architecture parameters into Richards equation-based models, introducing water stress indices to improve soil moisture predictions. However, for arid alpine mountain forest ecosystems, developing coupled models that integrate leaf-scale physiology, above- and below-ground responses, root dynamics, soil moisture, stand responses, and physical hydrology remains challenging due to parameterization and calibration difficulties at large spatial scales.

3.4 Interactions and Feedbacks Between Climate Change and Ecohydrological Processes Research on climate and ecohydrological processes requires multi-factor, multi-scale observations to collect and describe status information of various elements at different scales, thereby obtaining fundamental scientific understanding of surface processes. To accurately predict and quantitatively study climate change impacts on ecohydrological processes and conduct quantitative research on watershed parameters and hydrological responses, coupled models integrating climate, hydrological, and ecological processes are needed. Distributed ecohydrological models have simulated hydrological processes and vegetation dynamics in the upper Heihe River Basin, revealing that actual ET spatial patterns are primarily controlled by precipitation and temperature, with vegetation distribution further enhancing spatial variability. However, most studies have been conducted at single scales. Fully determining ecosystem responses to climate change requires complex models that combine leaf-scale physiology, stand responses, and physical hydrology, which are difficult to parameterize and calibrate at large scales. This necessitates developing coupled models of climate, hydrological, and ecological processes with interactions and feedbacks across different spatiotemporal scales.

4. Future Perspectives

Mounting evidence demonstrates that climate change plays a crucial role in controlling the water cycle by affecting soil moisture, evaporation, transpiration, and runoff. However, arid alpine mountain ecosystems (such as the Qilian Mountains) are highly sensitive and responsive to climate change, and research on impact mechanisms remains in its infancy with insufficient quantitative results. Current ecohydrological process research in high-altitude arid mountains has focused primarily on soil moisture dynamics, canopy structure-interception relationships, plant transpiration and its influencing factors, and precipitation impacts on forest water yields. Studies on climate change impacts on ecosystem stability have examined phenology, treelines, radial growth of Qinghai spruce, terrestrial primary productivity, ET changes, canopy position-climate-growth relationships, and alpine plant communities, but comprehensive studies integrating climate change impacts on both forest ecosystem stability and ecohydrological processes are lacking.

Looking forward, climate change research in arid mountains must evaluate trends at spatial resolutions finer than 1 km to provide managers with theoretical foundations for climate adaptation. Studies on interactions between climate change and forest ecosystem stability and ecohydrological processes should adopt multi-scale (plot, slope, watershed; individual, community, ecosystem) and multi-interface (vegetation-soil, soil-atmosphere) approaches across multiple disciplines (soil science, hydrology, ecology). Methods should include flux observation, sap flow techniques, radar technology, field simulation experiments, remote sensing, and modeling to elucidate mechanisms and predict future trends. This integrated approach will promote the development of mountain ecology in arid regions, provide theoretical foundations for climate adaptation and mitigation, and support sustainable environmental and socioeconomic development.

References

[1] IPCC. Summary for policymakers[C]//Stocker T F, Qin D, Plattner G K, et al. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 2013.

[2] IPCC. Global warming of 1.5 ℃[C]//Masson Delmotte V, Zhai P, Pörtner H, et al. An IPCC Special Report on the Impacts of Global Warming of 1.5 ℃ Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. Cambridge: Cambridge University Press, 2018.

[3] IPCC. Summary for policymakers[C]//Masson Delmotte V, Zhai P, Pirani A, et al. Climate Change 2021: The Physical Science Basis: Contribution of Working Group I to the Sixth Assessment Report, of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 2021.

[4] Qin D, Plattner G K, Tignor M, et al. Climate change 2013: The physical science basis[M]. Cambridge: Cambridge University Press, 2014.

[5] Kelley C P, Mohtadi S, Cane M A, et al. Climate change in the Fertile Crescent and implications of the recent Syrian drought[J]. Proceedings of the National Academy of Sciences of the United States of America, 2015, 112: 3241-3246.

[6] SIWI (Stockholm International Water Institute). Managing the forest-water nexus: Opportunities for climate change mitigation and adaptation[R]. 2019. https://www.siwi.org/publications/managing-forest-water-nexus/.

[7] Wang T. Some issues on oasification study in China[J]. Journal of Desert Research, 2010, 30(5): 995-998.

[8] Wang J, Yu P, Wang Y. Study on forest ecohydrological process: A case study of water conservation forest in Qilian Mountains, Gansu Province[M]. Beijing: Science Press, 2008.

[9] Ehbrecht M, Seidel D, Annighöfer P, et al. Global patterns and climatic controls of forest structural complexity[J]. Nature Communications, 2021, 12: 519, doi: 10.1038/s41467-020-20767-z.

[10] Ali A, Sanaei A, Li M, et al. Impacts of climatic and edaphic factors on the diversity, structure and biomass of species poor and structurally complex forests[J]. Science of the Total Environment, 2020, 706: 135719, doi: 10.1016/j.scitotenv.2019.135719.

[11] Gazol A, Camarero J J, Vicente-Serrano S M, et al. Forest resilience to drought varies across biomes[J]. Global Change Biology, 2018, 24: 2143-2158.

[12] Vose J M, Miniat C F, Luce C H, et al. Ecohydrological implications of drought for forests in the United States[J]. Agricultural and Forest Meteorology, 2016, 380: 335-345.

[13] Li B, Chen Y, Shi X, et al. Temperature and precipitation changes in different environments in the arid region of northwest China[J]. Theoretical and Applied Climatology, 2013, 112(3/4): 589-596.

[14] Yao J, Yang Q, Liu Z, et al. Spatio-temporal change of precipitation in arid region of the northwest China[J]. Acta Ecologica Sinica, 2015, 35(17): 5846-5855.

[15] Wang Y, Jia W, Liu C, et al. Ecological environment change in the north slope of the Qilianshan Mountains[J]. Scientia Silvae Sinicae, 2012, 48(4): 21-26.

[16] Cheng P, Kong X, Luo H, et al. Climate change and its runoff response in the middle section of the Qilian Mountains in the past 60 years[J]. Arid Land Geography, 2020, 43(5): 1192-1201.

[17] Wen Y, Lü Y, Li Z. Changes of extreme precipitation in Qilian Mountains in recent 60 years[J]. Arid Land Geography, 2021, 44(5): 1199-1212.

[18] Huang J, Yu H, Dai A, et al. Drylands face potential threat under 2 ℃ global warming targets[J]. Nature Climate Change, 2017, 7: 417-422.

[19] Nadeau C P, Urban M C, Bridle J R. Climates past, present, and yet-to-come shape climate change vulnerabilities[J]. Trends in Ecology & Evolution, 2017, 32: 786-800.

[20] Gaines W L, Hessburg P F, Aplet G H, et al. Climate change and forest management on federal lands in the Pacific Northwest, USA: Managing for dynamic landscapes[J]. Forest Ecology and Management, 2022, 504: 119794, doi: 10.1016/j.foreco.2021.119794.

[21] Teng M, Zeng L, Hu W, et al. The impacts of climate changes and human activities on net primary productivity vary across an ecotone zone in northwest China[J]. Science of the Total Environment, 2020, 714: 136691, doi: 10.1016/j.scitotenv.2020.136691.

[22] He Z, Du J, Chen L, et al. Impacts of recent climate extremes on spring phenology in arid mountain ecosystems in China[J]. Agricultural and Forest Meteorology, 2018, 260-261: 31-40.

[23] Jia W, Zhao Z, Zu J, et al. Phenological variation in different vegetation types and their response to climate change in the Qilian Mountains, China, 1982–2014[J]. Acta Ecologica Sinica, 2016, 36(23): 7826-7840.

[24] Gao L, Gou X, Deng Y, et al. Increased growth of Qinghai spruce in northwestern China during the recent warming hiatus[J]. Agricultural and Forest Meteorology, 2018, 260-261: 9-16.

[25] He Z, Zhao W, Zhang L, et al. Response of tree recruitment to climatic variability in the alpine treeline ecotone of the Qilian Mountains, northwestern China[J]. Forest Science, 2013, 59(1): 118-126.

[26] Hutchison C, Gravel D, Guichard F, et al. Effect of diversity on growth, mortality, and loss of resilience to extreme climate events in a tropical planted forest experiment[J]. Scientific Reports, 2018, 8(1): 15443, doi: 10.1038/s41598-018-33670-x.

[27] McDowell N G, Allen C D, Anderson-Teixeira K, et al. Pervasive shifts in forest dynamics in a changing world[J]. Science, 2020, 368: eaaz9463, doi: 10.1126/science.aaz9463.

[28] Wu X, Liu H, Li X, et al. Differentiating drought legacy effects on vegetation growth over the temperate Northern Hemisphere[J]. Global Change Biology, 2018, 24: 504-516.

[29] Vachaud G, de Silans A P, Balabanis P, et al. Temporal stability of spatially measured soil water probability density function[J]. Soil Science Society America Journal, 1985, 49: 822-828.

[30] De Keersmaecker W, Lhermitte S, Tits L, et al. A model quantifying global vegetation resistance and resilience to short-term climate anomalies and their

relationship with vegetation cover[J]. Global Ecology & Biogeography, 2015, 24: 539-548.

[31] Pennekamp F, Pontarp M, Tabi A, et al. Biodiversity increases and decreases ecosystem stability[J]. Nature, 2018, 563: 109-112.

[32] Huang K, Xia J. High ecosystem stability of evergreen broadleaf forests under severe droughts[J]. Global Change Biology, 2019, 25: 1067-1077.

[33] Ouyang S, Xiang W, Gou M, et al. Stability in subtropical forests: The role of tree species diversity, stand structure, environmental and socio-economic conditions[J]. Global Ecology and Biogeography, 2021, 30: 500-513.

[34] Li D, Wu S, Liu L, et al. Vulnerability of the global terrestrial ecosystems to climate change[J]. Global Change Biology, 2018, 24: 2375-2384.

[35] Eller C, Burgess S, Oliveira R. Environmental controls in the water use patterns of a tropical cloud forest tree species, Drimys brasiliensis (Winteraceae)[J]. Tree Physiology, 2015, 35: 387-399.

[36] Hegerl G C, Black E, Allan R P, et al. Challenges in quantifying changes in the global water cycle[J]. Bulletin of the American Meteorological Society, 2015, 96: 1097-1115.

[37] Zhang K, Kimball J S, Nemani R R, et al. Vegetation greening and climate change promote multidecadal rises of global land evapotranspiration[J]. Scientific Reports, 2015, 5: 15956, doi: 10.1038/srep15956.

[38] Kim Y, Band L E, Ficklin D L. Projected hydrological changes in the North Carolina piedmont using bias-corrected North American Regional Climate Change Assessment Program (NARCCAP) data[J]. Journal of Hydrology: Regional Studies, 2017, 12: 273-288.

[39] Ma X. Forest hydrology[M]. Beijing: China Forestry Publishing House, 1993.

[40] Liu S. A new model for the prediction of rainfall interception in forest canopies[J]. Ecological Modelling, 1997, 99(2): 151-159.

[41] Gash J H C. An analytical model of rainfall interception by forests[J]. Quarterly Journal of the Royal Meteorological Society, 1979, 105: 43-55.

[42] Eliades M, Bruggeman A, Djuma H, et al. Testing three rainfall interception models and different parameterization methods with data from an open Mediterranean pine forest[J]. Agricultural and Forest Meteorology, 2022, 313: 108755, doi: 10.1016/j.agrformet.2021.108755.

[43] Vereecken H, Pachepsky Y, Simmer C, et al. On the role of patterns in understanding the functioning of soil-vegetation-atmosphere systems[J]. Journal of Hydrology, 2016, 542: 63-86.

[44] Fatichi S, Katul G G, Ivanov V Y, et al. Abiotic and biotic controls of soil moisture spatiotemporal variability and the occurrence of hysteresis[J]. Water

Resources Research, 2015, 51: 3505-3524.

[45] Liu Q, Hao Y, Stebler E, et al. Impact of plant functional types on coherence between precipitation and soil moisture: A wavelet analysis[J]. Geophysical Research Letters, 2017, 44: 12197-12207.

[46] Gonzalez-Ollauri A, Stokes A, Mickovski S B. A novel framework to study the effect of tree architectural traits on stemflow yield and its consequences for soil water dynamics[J]. Journal of Hydrology, 2020, 582: 124448, doi: 10.1016/j.jhydrol.2019.124448.

[47] Agee E, He L, Bisht G, et al. Root lateral interactions drive water uptake patterns under water limitation[J]. Advances in Water Resources, 2021, 151: 103896, doi: 10.1016/j.advwatres.2021.103896.

[48] Zeng Z, Peng L, Piao S. Response of terrestrial evapotranspiration to Earth' s greening[J]. Current Opinion in Environmental Sustainability, 2018, 33: 9-25.

[49] Palmquist K A, Schlaepfer D R, Bradford J B, et al. Mid-latitude shrub steppe plant communities: Climate change consequences for soil water resources[J]. Ecology, 2016, 97(9): 2342-2354.

[50] Nouri M, Homaee M, Bannayan M. Quantitative trend, sensitivity and contribution analyses of reference evapotranspiration in some arid environments under climate change[J]. Water Resources Management, 2017, 31: 2207-2224.

[51] da Costa A C L, Rowland L, Oliveira R S. Stand dynamics modulate water cycling and mortality risk in droughted tropical forest[J]. Global Change Biology, 2018, 24: 249-258.

[52] Fatichi S, Pappas C, Ivanov V Y. Modeling plant-water interactions: An ecohydrological overview from the cell to the global scale[J]. Wiley Interdisciplinary Reviews: Water, 2016, 3: 327-368.

[53] Ning T, Li Z, Feng Q, et al. Effects of forest cover change on catchment evapotranspiration variation in China[J]. Hydrological Processes, 2020, 34: 2219-2228.

[54] Wang L, Liu Z, Guo J, et al. Estimate canopy transpiration in larch plantations via the interactions among reference evapotranspiration, leaf area index, and soil moisture[J]. Forest Ecology and Management, 2021, 481: 118749, doi: 10.1016/j.foreco.2020.118749.

[55] Yang L, Feng Q, Adamowski J F, et al. The role of climate change and vegetation greening on the variation of terrestrial evapotranspiration in northwest China' s Qilian Mountains[J]. Science of the Total Environment, 2021, 759: 143532, doi: 10.1016/j.scitotenv.2020.143532.

[56] Song X, Gao X, Dyck M, et al. Soil water and root distribution of apple tree (Malus pumila Mill) stands in relation to stand age and rainwater collection and infiltration system (RWCI) in a hilly region of the Loess Plateau, China[J]. Catena, 2018, 170: 324-334.

[57] Zhang T, Song L, Zhu J, et al. Spatial distribution of root systems of Pinus sylvestris mongolica trees with different ages in a semi-arid sandy region of northeast China[J]. Forest Ecology and Management, 2021, 483: 118776, doi: 10.1016/j.foreco.2020.118776.

[58] Manoli G, Bonetti S, Domec J, et al. Tree root systems competing for soil moisture in a 3D soil-plant model[J]. Advances in Water Resources, 2014, 66: 32-42.

[59] Yang Y, Guan H, Hutson J L, et al. Examination and parameterization of the root water uptake model from stem water potential and sap flow measurements[J]. Hydrological Processes, 2013, 27: 2855-2863.

[60] Peters A. Modified conceptual model for compensated root water uptake: A simulation study[J]. Journal of Hydrology, 2016, 534: 1-12.

[61] Bouda M, Saiers J E. Dynamic effects of root system architecture improve root water uptake in 1-D process-based soil-root hydrodynamics[J]. Advances in Water Resources, 2017, 110: 319-334.

[62] Ding Y. Scientific report on monitoring key factors of surface in cold and arid regions of China[M]. Beijing: China Meteorological Press, 2015.

[63] Gao B, Qin Y, Wang Y, et al. Modeling ecohydrological processes and spatial patterns in the upper Heihe Basin in China[J]. Forests, 2016, 7(1): 10, doi: 10.3390/f7010010.

[64] Paschalis A, Katul G G, Fatichi S, et al. Matching ecohydrological processes and scales of banded vegetation patterns in semiarid catchments[J]. Water Resources Research, 2016, 52: 2259-2278.

[65] Tang G, Carroll R W H, Lutz A, et al. Regulation of precipitation-associated vegetation dynamics on catchment water balance in a semiarid and arid mountainous watershed[J]. Ecohydrology, 2016, 9: 1248-1262.

[66] Montaldo N, Oren R. Rhizosphere water content drives hydraulic redistribution: Implications of pore-scale heterogeneity to model diurnal transpiration in water-limited ecosystems[J]. Agricultural and Forest Meteorology, 2022, 312: 108720, doi: 10.1016/j.agrformet.2021.108720.

[67] Tague C L, Choate J S, Grant G. Parameterizing sub-surface drainage with geology to improve modeling streamflow responses to climate in data-limited environments[J]. Hydrology and Earth System Sciences, 2013, 17: 341-354.

[68] Liu H, Zhao W, He Z, et al. Soil moisture dynamics across landscape types in an arid inland river basin of northwest China[J]. Hydrological Processes, 2015, 29: 3328-3341.

[69] He Z, Yang J, Du J, et al. Spatial variability of canopy interception in a spruce forest of the semiarid mountain regions of China[J]. Agricultural and Forest Meteorology, 2014, 188: 58-63.

[70] Chang X, Zhao W, He Z. Radial pattern of sap flow and response to microclimate and soil moisture in Qinghai spruce (Picea crassifolia) in the upper Heihe River Basin of arid northwestern China[J]. Agricultural and Forest Meteorology, 2014, 187: 14-21.

[71] Chang X, Zhao W, Liu H, et al. Qinghai spruce (Picea crassifolia) forest transpiration and canopy conductance in the upper Heihe River Basin of arid northwestern China[J]. Agricultural and Forest Meteorology, 2014, 198-199: 209-220.

[72] Chang X, Zhao W, Liu B, et al. Can forest water yields be increased with increased precipitation in a Qinghai spruce forest in arid northwestern China?[J]. Agricultural and Forest Meteorology, 2017, 247: 139-150.

[73] Li Y, Chen Q, He K, et al. The accuracy improvement of sap flow prediction in Picea crassifolia Kom based on the back propagation neural network model[J]. Hydrological Processes, 2022, 36(2): e14490, doi: 10.1002/hyp.14490.

[74] Li X, Vereecken H. Observation and measurement of ecohydrological processes[M]. Berlin: Springer, 2019: 417-433.

[75] Du J, He Z, Chen L, et al. Interacting effects of temperature and precipitation on climatic sensitivity of spring vegetation green-up in arid mountains of China[J]. Agricultural and Forest Meteorology, 2019, 269-270: 71-77.

[76] Tian Q, He Z, Xiao S, et al. Effects of artificial warming on stem radial changes in Qinghai spruce saplings in the Qilian Mountains of China[J]. Dendrochronologia, 2019, 55: 110-118.

[77] Xu H, Zhao C, Wang X. Spatiotemporal differentiation of the terrestrial gross primary production response to climate constraints in a dryland mountain ecosystem of northwestern China[J]. Agricultural and Forest Meteorology, 2019, 276-277: 107628, doi: 10.1016/j.agrformet.2019.107628.

[78] Wang B, Yu P, Yu Y, et al. Effects of canopy position on climate-growth relationships of Qinghai spruce in the central Qilian Mountains, northwestern China[J]. Dendrochronologia, 2020, 64: 125756, doi: 10.1016/j.dendro.2020.125756.

[79] Du J, He Z, Chen L, et al. Impact of climate change on alpine plant community in Qilian Mountains of China[J]. International Journal of Biometeorology, 2021, 65: 1849-1858.

Note: Figure translations are in progress. See original paper for figures.