A 10 m resolution land cover map of the Tibetan Plateau with detailed vegetation types

Community Referee #1

General comments:

This study proposes a 10 m resolution land cover map of the Tibetan Plateau with detailed vegetation types. The experimental design is thorough. However, I have some concerns.

Response: We are grateful for your kind acknowledgment of the experimental design of our study and thank you for providing insightful comments and detailed suggestions. Following your constructive feedback, we have revised the text to strengthen the clarity and accuracy of this manuscript.

Specific comments:

1. **Line 89: Precipitation data is 0.05degree resolution, can the resampled 10m data maintain the quality?**

Reply 1:

The quality of resampled climate data is sufficient for the classification. Climate data contributes to the classification process mainly at the regional scale, for example, southeast TP is more humid than the middle and east parts of TP. At the local scale, satellite imagery and topography data play a dominant role in the classification process, while the contribution from climate data to classification is minimal. Besides, our product shows consistent finer spatial patterns at 10m resolution. For clarification, we have elaborated on this issue in the revised manuscript (Lines 255-258), which reads:

The TP exhibits significant variations in annual rainfall and land surface temperature across its diverse regions, resulting in distinct hot and cold spots (Rao et al., 2019; Wu et al., 2019). Leveraging climate data can thus prove beneficial in categorizing alpine meadows in the southeastern TP and alpine grasslands in the northwestern TP at regional climatic scales, given their high sensitivity to changes in annual precipitation and land surface temperature (Su et al., 2020; Y. Wang et al., 2021).

Reference:

Rao, Y., Liang, S., Wang, D., Yu, Y., Song, Z., Zhou, Y., Shen, M., & Xu, B. (2019). Estimating daily average surface air temperature using satellite land surface temperature and top-of-atmosphere radiation products over the Tibetan Plateau. Remote Sensing of Environment, 234, 111462. https://doi.org/10.1016/j.rse.2019.111462

Su, Y., Guo, Q., Hu, T., Guan, H., Jin, S., An, S., Chen, X., Guo, K., Hao, Z., Hu, Y., Huang, Y., Jiang, M., Li, J., Li, Z., Li, X., Li, X., Liang, C., Liu, R., Liu, Q., … Ma, K. (2020). An updated Vegetation Map of China (1:1000000). Science Bulletin, 65(13), 1125–1136. https://doi.org/10.1016/j.scib.2020.04.004

Wang, Y., Xiao, J., Ma, Y., Luo, Y., Hu, Z., Li, F., Li, Y., Gu, L., Li, Z., & Yuan, L. (2021). Carbon fluxes and environmental controls across different alpine grassland types on the Tibetan Plateau. Agricultural and Forest Meteorology, 311, 108694. https://doi.org/10.1016/j.agrformet.2021.108694

Wu, Y., Guo, L., Zheng, H., Zhang, B., & Li, M. (2019). Hydroclimate assessment of gridded precipitation products for the Tibetan Plateau. Science of The Total Environment, 660, 1555–1564. https://doi.org/10.1016/j.scitotenv.2019.01.119

2. Line 90: What is the spatial resolution of temperature data?

Reply 2:

The spatial resolution of temperature data is 0.1degree. We also added this information to our revised manuscript (Line 103).

3. Line 116-117: Why combine bare land and impervious area? Because other land cover products usually separate these two classes.

Reply 3:

Thanks for pointing this out. We have added an explanation and discussed this issue in our revised manuscript (Lines 132-136 and 266-268).

Line 132-136:

In this study, we did not specifically select samples of built-up areas and instead categorized bare land together with built-up areas for two primary reasons. Firstly, built-up areas account for only 0.092% of the total area in ESA WorldCover2021, highlighting their relatively small extent compared to other land cover types (Zanaga et al., 2022). Secondly, bare land in our product exhibits spectral characteristics similar to those of built-up areas, resulting in the classification of most built-up areas as bare land (H. Li et al., 2017).

Lines 266-270:

In addition , the spectral variations within urban areas have also resulted in substantial uncertainties. Our approach of categorizing built-up areas and bare land may lead to misclassification of urban pixels. To minimize the uncertainties in urban areas on our final map, we applied the ESRI land cover map in 2022 to mask off urban pixels (Karra et al., 2021).

Reference:

Karra, K., Kontgis, C., Statman-Weil, Z., Mazzariello, J. C., Mathis, M., & Brumby, S. P.

(2021). Global land use / land cover with Sentinel 2 and deep learning. 2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS, 4704–4707. https://doi.org/10.1109/IGARSS47720.2021.9553499

Li, H., Wang, C., Zhong, C., Su, A., Xiong, C., Wang, J., & Liu, J. (2017). Mapping Urban Bare Land Automatically from Landsat Imagery with a Simple Index. Remote Sensing, 9(3), 249. https://doi.org/10.3390/rs9030249

Zanaga, D., Van De Kerchove, R., Daems, D., De Keersmaecker, W., Brockmann, C., Kirches, G., Wevers, J., Cartus, O., Santoro, M., Fritz, S., Lesiv, M., Herold, M., Tsendbazar, N.-E., Xu, P., Ramoino, F., and Arino, O.: ESA WorldCover 10 m 2021 v200, Zenodo [data set], https://doi.org/10.5281/zenodo.5571936, 2022

4. **Line 165: As the vegetation will be affected by seasons, have you considered getting the median composites of Sentinel data for each season, and then combining all seasons as the input?**

Reply 4:

We considered combining the four seasons as the input. However, generating seasonal composites requires acquiring high-quality Sentinel-2 time series images, which is challenging in the TP. For instance, lowering the threshold of cloud filtering results in the reduction of image pixels available for analysis, particularly in the southeastern TP, where has heavy cloud contamination (Tang et al., 2022). Conversely, raising this threshold to a higher level compromises the quality control of Sentinel-2 images while maintaining image integrity. We have included a quantitative discussion on this matter in the revised manuscript (Lines 273-278), which reads:

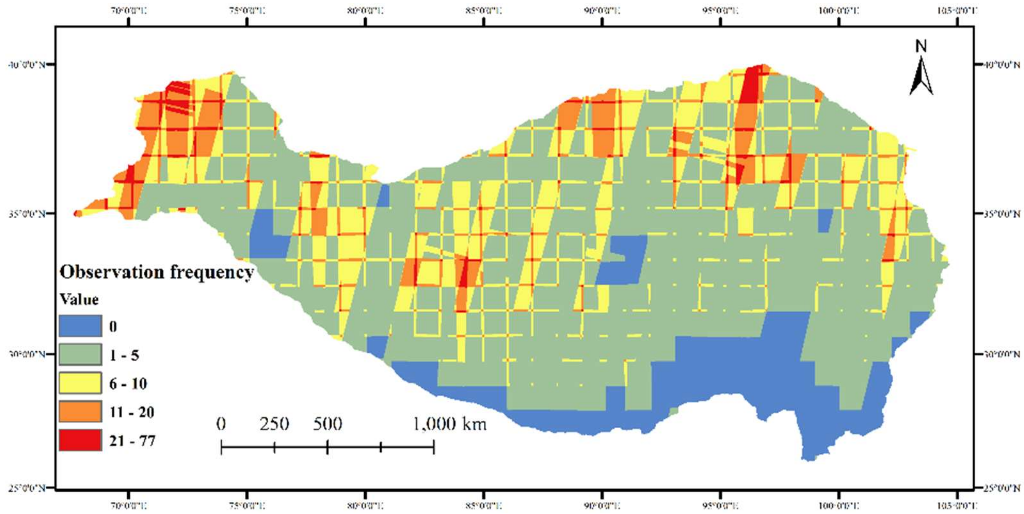

Figure A3. Number of available observations for the Sentinel-2 optical data in the Tibetan Plateau during summer in 2022 (June 1, 2022, to August 31, 2022) with cloud cover <10%.

For example, during the summer of 2022 (June-August), when setting the "CLOUDY_PIXEL_PERCENTAGE" parameter to 10%, 20%, 30%, and 40%, and applying QA band masking, we lost 13.59%, 5.81%, 2.44%, and 1.32% of the Sentinel-2 image area in the TP. The removed pixels are concentrated mainly in the *cloudy southeastern TP (only shown for 10% threshold in Fig. A3) (Tang et al., 2022). This constraint can preclude the attainment of desired outcomes in regions where cloud-free image availability is low (Chu et al., 2021; Coluzzi et al., 2018).*

Reference:

Chu, D., Shen, H., Guan, X., Chen, J. M., Li, X., Li, J., & Zhang, L. (2021). Long time-series NDVI reconstruction in cloud-prone regions via spatio-temporal tensor completion. Remote Sensing of Environment, 264, 112632. https://doi.org/10.1016/j.rse.2021.112632

Coluzzi, R., Imbrenda, V., Lanfredi, M., & Simoniello, T. (2018). A first assessment of the Sentinel-2 Level 1-C cloud mask product to support informed surface analyses. Remote Sensing of Environment, 217, 426–443.

Tang, J., Guo, X., Chang, Y., Lu, G., & Qi, P. (2022). Long-term variations of clouds and precipitation on the Tibetan Plateau and its subregions, and the associated mechanisms. International Journal of Climatology, 42(16), 9003–9022. https://doi.org/10.1002/joc.7792

5. **Line 180: This study is based on pixel-based machine learning classification models. The pixel-based approach tends to produce classification with a salt-pepper effect, did you do any post-classification to remove the noise?**

Reply 5:

Thank you for raising this concern. We did not perform any post-classification noise removal methods. The TP exhibits highly heterogeneous vegetation landscapes. Applying image smoothing techniques to eliminate noise may not accurately represent the diverse distribution of vegetation types and could lead to a loss of detailed edge information.

6. **Line 185: Why not use the major voting results of all models as the final results?**

Reply 6:

We selected the model with best performance to ensure consistency in our final map across the entire TP, while different model exhibit variations in the classification performance for different land cover types, choosing appropriate weights for each model might be challenging.

7. **Line 245: Have you considered comparing the area in each land cover between your classification and other land cover products?**

Reply 7:

Thank you for this valuable suggestion. We have included a new table in the revised manuscript to address this aspect.

Line 246-247:

Table A4 presents the statistical results of 5 land cover products in the TP, highlighting significant discrepancies among them.

Table A4. Area statistical results for land cover products in the Tibetan Plateau.

	TP_LC10-2022		FROM_GLC30-2015		GLC_FCS30-2020		WorldCover2021		FROM_GLC10-2017	
Land cover type	Area	Proportion	Area	Proportion	Area	Proportion	Area	Proportion	Area	Proportion
BL	58.75	19.05%	147.67	47.89%	45.71	14.82%	134.75	43.70%	156.45	50.74%
AG	50.83	16.48%	96.75	31.38%	189.44	61.44%	108.44	35.17%	89.35	28.98%
AM	73.25	23.76%								
ENF	11.44	3.71%	27.91	9.05%	31.52	10.22%				
DNF	2.26	0.73%	0.02	0.01%	0.37	0.12%				
EBF	4.53	1.47%	2.94	0.95%	3.45	1.12%	28.49	9.24%	29.46	9.55%
DBF	6.80	2.20%	1.69	0.55%	4.31	1.40%				
MF	1.46	0.47%	4.10	1.33%	0.00	0.00%				
ES	3.28	1.06%	1.70	0.55%	0.22	0.07%	0.37	0.12%	1.59	0.51%
DS	11.02	3.57%	0.41	0.13%	4.13	1.34%				
WB	6.43	2.09%	12.38	4.02%	6.05	1.96%	6.86	2.22%	10.06	3.26%
WL	6.84	2.22%	0.19	0.06%	0.55	0.18%	0.37	0.12%	2.06	0.67%
CV	5.14	1.67%	2.04	0.66%	2.81	0.91%	1.35	0.44%	3.02	0.98%
PIS	23.18	7.52%	10.46	3.39%	19.08	6.19%	12.95	4.20%	16.36	5.30%
AS / Tundra / Lichen / Moss	43.15	13.99%	0.05	0.01%	0.00	0.00%	14.77	4.79%	0.00	0.00%
Total	308.34	100.00%	308.31	99.99%	307.66	99.78%	308.34	100.00%	308.34	100.00%

BL: bare land; AG: alpine grassland; AM: alpine meadow; ENF: evergreen needle-leaved forest; DNF: deciduous needle-leaved forest; EBF: evergreen broadleaved forest; DBF: deciduous broadleaved forest; MF: mixed forest; ES: evergreen shrubland; DS: deciduous shrubland; WB: water body; WL: wetland; CV: cultivated vegetation; PIS: permanent ice and snow; AS: alpine scree

• The unit of area is ten thousand square kilometers, and the unit of proportion is percent.

• Please refer to Table A3 for the merging rules of land cover for FROM_GLC30-2015 and GLC_FCS30-2020.
• The 'cloud' class in the FROM_GLC30-2015 and 'shrubland' class in the GLC_FCS30-2020 product have been omitted from the table due to their small area.
• All built-up pixels are merged with bare land.

Also, we have strengthened the discussion using this table in the revised manuscript (Lines 251-254 and 322-328)

Lines 251-254:

GLC_FCS30-2020 exhibits the highest consistency with TP_LC10-2022 regarding bare land (Table A4 and Fig. 5), but it classified more areas as grasslands while failing to differentiate between grasslands and meadows. According to Fig. 5b, ESA WorldCover2021, FROM_GLC10-2017, and FROM_GLC30-2015 products overestimate the area of bare land in the TP, similar to the issues observed in FROM_GLC-agg and ESA CCI land cover products (Liu et al., 2021; L. Yu et al., 2014). This may be due to the misclassification of alpine grassland as bare land because these products captured less spectral information during the growing season of alpine grasslands. GLC_FCS30-2020 exhibits the highest consistency with TP_LC10-2022 regarding bare land (Table A4 and Fig. 5) and it classified more grasslands while failed to differentiate between grasslands and meadows. Additionally, GLC_FCS30-2020 assigns 61.44% of the total TP area as grassland, indicating an overestimation of grassland extent (Table A4).

Lines 320-326:

Alpine forests play a crucial role in carbon storage and sequestration, thereby enhancing ecosystem services in the TP (Lin et al., 2023; Z. Wang et al., 2022; H. Zhao et al., 2023). Our study revealed that TP_LC10-2022 identified the smallest forested area (8.60%), while GLC_FCS30-2020 and FROM_GLC30-2015 classified the largest and second-largest areas of alpine forest, respectively (12.86% and 11.89%) (Table A4). Conversely, the area of shrubland exhibits nearly the opposite trend (Table A4). Confusion also arises between alpine grassland and bare land, potentially leading to variations in carbon storage estimation within each vegetation type. These discrepancies could impact efforts related to forest resource protection and grassland management for animal husbandry (J. Li et al., 2020; C. Yu et al., 2022).

Reference:

Cheng, Y. (2021). Climate response to introduction of the ESA CCI land cover data to the NCAR CESM. Climate Dynamics, 56(11–12), 4109–4127. https://doi.org/10.1007/s00382-021-05690-3

Li, J., Gong, J., Guldmann, J.-M., Li, S., & Zhu, J. (2020). Carbon Dynamics in the

Northeastern Qinghai–Tibetan Plateau from 1990 to 2030 Using Landsat Land Use/Cover Change Data. Remote Sensing, 12(3), 528. https://doi.org/10.3390/rs12030528

Lin, Y., Xiao, J.-T., Kou, Y.-P., Zu, J.-X., Yu, X.-R., & Li, Y.-Y. (2023). Aboveground carbon sequestration rate in alpine forests on the eastern Tibetan Plateau: Impacts of future forest management options. Journal of Plant Ecology, 16(3), rtad001. https://doi.org/10.1093/jpe/rtad001

Wang, Z., Song, W., & Yin, L. (2022). Responses in ecosystem services to projected land cover changes on the Tibetan Plateau. Ecological Indicators, 142, 109228. https://doi.org/10.1016/j.ecolind.2022.109228

Yu, C., Xu, L., Li, M., & He, N. (2022). Phosphorus storage and allocation in vegetation on the Tibetan Plateau. Ecological Indicators, 145, 109636. https://doi.org/10.1016/j.ecolind.2022.109636

Yu, L., Wang, J., Li, X., Li, C., Zhao, Y., & Gong, P. (2014). A multi-resolution global land cover dataset through multisource data aggregation. Science China Earth Sciences, 57(10), 2317–2329. https://doi.org/10.1007/s11430-014-4919-z

Zhao, H., Guo, B., & Wang, G. (2023). Spatial–Temporal Changes and Prediction of Carbon Storage in the Tibetan Plateau Based on PLUS-InVEST Model. Forests, 14(7), 1352. https://doi.org/10.3390/f14071352

8. Authors need to elaborate on the discussion section using more references and describe the implications of your product for the sustainable use of available resources in practice, for policy, and research.

Reply 8:

Thank you for your constructive advice. We have elaborated our discussion in terms of its implications for policy, research, and the sustainable use of available resources in practice (Lines 312-340).

1. For sustainable use of available resources in practice:

Lakes and glaciers are the sentinels of global climate change and constitute the foundation of the TP as a crucial water source for surrounding regions (G. Zhang et al., 2017; G. Zhang & Duan, 2021). Precisely extracting the boundaries of lakes and glaciers is imperative for quantitatively monitoring lake expansion and glacier melting, as well as understanding the dynamic relationship between them and precipitation (Tong et al., 2016; J. Zhang et al., 2021; R. Zhao et al., 2022). Our land cover data, samples, and mapping methodology can serve as a baseline support for these endeavors (Korzeniowska & Korup, 2017; Yan et al., 2020), which facilitates the effective utilization of available water resources and promotes the sustainable development of the economy and society in the Greater Tibetan Plateau area and downstream regions of rivers originating from the TP (Ding et al., 2019).

2. For policy making:

Alpine forests play a crucial role in carbon storage and sequestration, thereby enhancing ecosystem services in the TP (Lin et al., 2023; Z. Wang et al., 2022; H. Zhao et al., 2023). Our study revealed that TP_LC10-2022 identified the smallest forested area (8.60%), while GLC_FCS30-2020 and FROM_GLC30-2015 classified the largest and second-largest areas of alpine forest, respectively (12.86% and 11.89%) (Table A4). Conversely, the area of shrubland exhibits nearly the opposite trend (Table A4). Confusion also arises between alpine grassland and bare land, potentially leading to variations in carbon storage estimation within each vegetation type. These discrepancies could impact efforts related to forest resource protection and grassland management for animal husbandry (J. Li et al., 2020; C. Yu et al., 2022).

3. **For further research:**

Alpine screes are extensively distributed across the TP, yet they are frequently disregarded from other products. Our product presents the initial description of alpine scree vegetation locations, which will contribute to environmental monitoring and biodiversity research in the periglacial zone of the TP (X.-H. Li et al., 2014). Shrublands play a vital role as carbon sinks in ecosystems and hold substantial implications for biomass estimation and global carbon cycling (Ma et al., 2021; Nie et al., 2018). TP_LC10-2022 accurately predicts the spatial distribution of shrublands, which holds considerable importance in forecasting the impact of future changes in the biomass and carbon cycle on global-scale ecosystems (Chang et al., 2022).

High-resolution and accurate land cover data encompassing diverse vegetation types are crucial for monitoring large-scale alpine vegetation dynamics (F. Wang et al., 2023; Z. Wang et al., 2020, 2022). For instance, relying on land cover maps such as ESA WorldCover as the foundation to examine tree lines and vegetation lines in the TP may lead to the underestimation of tree lines due to misclassifications of grasslands and shrublands (Fig. 7) (Zou et al., 2023). Additionally, the vegetation line may also be underestimated because of the absence of alpine scree (Fig. 7). In our future work, we aim to leverage the Sentinel-2, Sentinel-1, and other multisource data to annually generate TP_LC10 products. This approach will facilitate alpine vegetation monitoring and change detection, thereby enriching our comprehension of the dynamic TP amidst intensifying global climate change (Y. Wang et al., 2022).

References:

Chang, Q., Zwieback, S., DeVries, B., & Berg, A. (2022). Application of L-band SAR for mapping tundra shrub biomass, leaf area index, and rainfall interception. Remote Sensing of Environment, 268, 112747. https://doi.org/10.1016/j.rse.2021.112747

Ding, X., Zhang, Z., Wu, F., & Xu, X. (2019). Study on the Evolution of Water Resource Utilization Efficiency in Tibet Autonomous Region and Four Provinces in Tibetan

Areas under Double Control Action. Sustainability, 11(12), 3396. https://doi.org/10.3390/su11123396

Korzeniowska, K., & Korup, O. (2017). Object-Based Detection of Lakes Prone to Seasonal Ice Cover on the Tibetan Plateau. Remote Sensing, 9(4), 339. https://doi.org/10.3390/rs9040339

Li, J., Gong, J., Guldmann, J.-M., Li, S., & Zhu, J. (2020). Carbon Dynamics in the Northeastern Qinghai–Tibetan Plateau from 1990 to 2030 Using Landsat Land Use/Cover Change Data. Remote Sensing, 12(3), 528. https://doi.org/10.3390/rs12030528

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Tong, K., Su, F., & Xu, B. (2016). Quantifying the contribution of glacier meltwater in the expansion of the largest lake in Tibet. Journal of Geophysical Research: Atmospheres, 121(19). https://doi.org/10.1002/2016JD025424

Wang, F., Ma, Y., Darvishzadeh, R., & Han, C. (2023). Annual and Seasonal Trends of Vegetation Responses and Feedback to Temperature on the Tibetan Plateau since the 1980s. Remote Sensing, 15(9), 2475. https://doi.org/10.3390/rs15092475

Wang, Y., Li, D., Ren, P., Ram Sigdel, S., & Camarero, J. J. (2022). Heterogeneous Responses of Alpine Treelines to Climate Warming across the Tibetan Plateau. Forests, 13(5), 788. https://doi.org/10.3390/f13050788

Wang, Z., Song, W., & Yin, L. (2022). Responses in ecosystem services to projected land cover changes on the Tibetan Plateau. Ecological Indicators, 142, 109228. https://doi.org/10.1016/j.ecolind.2022.109228

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Yan, D., Huang, C., Ma, N., & Zhang, Y. (2020). Improved Landsat-Based Water and Snow Indices for Extracting Lake and Snow Cover/Glacier in the Tibetan Plateau. Water, 12(5), 1339. https://doi.org/10.3390/w12051339

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