# Disentangling linkages between satellite derived forest structure and productivity across a range of forest types and ecosystems.

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**Abstract**

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*Keywords:* structural equation modelling, remote sensing, landsat, forest structure, forest productivity

## 1. Introduction

Biodiversity is the summation of variation in biological life, across genes, species, communities, and ecosystems. Currently, biodiversity is in decline, facing extinction rates above the background extinction rate (Thomas et al., 2004; Urban, 2015), and homogenization of communities at various scales (McGill et al., 2015). In response, the global biodiversity community is making efforts to assess and halt the degradation of biodiversity on earth. The Group for Earth Observation Biodiversity Observation Network has developed the Essential Biodiversity Variables (EBVs, Pereira et al., 2013), designed as an analog to the Essential Climate Variables framework (Bojinski et al., 2014). EBVs are designed to be global in scope, relevant to biodiversity information, feasible to utilize, and complementary to one another (Skidmore et al., 2021).

There are six EBV classes, each corresponding to a different facet of biodiversity, including, genetic composition, species populations, species traits, community composition, ecosystem structure, and ecosystem function (Pereira et al., 2013). Fernán-

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dez et al. (2020) divides the six classes into two approaches, with one focusing on species biodiversity, and the other focusing on ecosystem diversity. Remote sensing has proven to be capable of measure five of the six classes, with the exception being genetic composition, which requires in-situ observation and samples (Skidmore et al., 2021). Notably, while remote sensing can provide information on the remaining two species EBV classes, this information is typically acquired with an *ad-hoc* approach. This collects high resolution, small spatial extent information, rather than the global or regional scales required for biodiversity assessment. Community composition falls into a similar dilemma, requiring species population information which necessitates high resolution spatial data.

The remaining two classes, ecosystem structure and function, are incredibly well suited to be examined at global or regional scales using mid-resolution satellite imagery, such as that provided by the Landsat series of satellites. Advances in satellite remote sensing processing have allowed 3d forest structure data to be imputed across wide spatial scales (Matasci et al., 2018; Coops et al., 2021) using data fusion approaches involving collected lidar data and optical/radar data. Other advances in image compositing have allowed yearly summaries of vegetation productivity to be calculated at regional to global scales, summarizing the yearly energy totals, minimums, and variations (Radeloff et al., 2019). These datasets correspond quite well with the EBV classes ecosystem structure (forest structural diversity metrics), and ecosystem function (forest productivity metrics).

Forest structural diversity has been linked to biodiversity at various scales (Guo et al., 2017; Bergen et al., 2009; Gao et al., 2014). Increased structural complexity is hypothesized to create additional niches, leading to increased species diversity (Bergen et al., 2009). The relationship between forest structure and biodiversity is commonly assessed using avian species diversity metrics (Macarthur and Macarthur, 1961; Goetz et al., 2007), however, other clades (and habitats), have been used (Davies and Asner, 2014; Nelson et al., 2005). Many metrics derived from lidar remote sensing have been used as local indicators of biodiversity, including canopy cover, canopy height, vertical profiles, and aboveground biomass, while other 2nd order derived metrics such as canopy texture, height class distribution, edges, and patch metrics have been used to examine habitat and biodiversity at landscape scales (Bergen et al., 2009).

The dynamic habitat indices (DHIs) are indicators of productivity calculated by summarizing vegetation indices over the course of one (or multiple) years (Radeloff et al., 2019). These indices have been related to multiple facets of biodiversity at a range of scales, including species occurrence and abundance (Razenkova et al., 2020), alpha (Radeloff et al., 2019) and beta diversity (Andrew et al., 2012). Hypotheses behind the biodiversity productivity relationships have been established, including the species-energy hypothesis, the environmental stress hypothesis, and the environmental stability hypothesis (Coops et al., 2019). The cumulative DHI calculates the total amount of energy available in a given pixel over the course of a year. Cumulative DHI is strongly linked to the available energy hypothesis, which suggests that with greater available energy species richness will increase (Wright, 1983). The minimum DHI, which calculates the lowest productivity over the course of a year can be matched to the environmental stress hypothesis, which proposes that higher levels of minimum available energy will lead to higher species richness (Currie et al., 2004). Finally, the variation DHI, which calculates the coefficient of variance in a vegetation index through the course of a year, corresponds to the environmental stability hypothesis which states that lower energy variation throughout a year will lead to increased species richness (Williams and Middleton, 2008).

Linkages between forest structure and productivity (namely, vegetation indices) have been examined for nearly 20 years (Huete et al., 2002, Knyazikhin et al. (1998); Myneni and Williams, 1994). While there is significant theoretical and empirical evidence for their relationship at single time points (within a single image) (Myneni and Williams, 1994), various relationship directions and shapes have been found between forest structure and productivity metrics (Ali, 2019). These relationships, their shapes, and their strengths have been attributed to multiple possible hypotheses and can vary based on environmental conditions (Ali, 2019). The relationship between forest structural diversity metrics and annual productivity summaries has yet to be fully examined, including the DHIs.

Some vegetation structure metrics are simpler, and more accurate, to calculate than others (Coops et al., 2021). These basic metrics, such as canopy height and canopy cover,can then be used to estimate additional structure metrics, such as basal area or total biomass. Canopy height and cover are commonly used as an indicator of vertical and horizontal variation, respectively. Recently, more attention has been paid to internal structural complexity metrics, which can be more difficult and time consuming to generate (Coops et al., 2021; Ma et al., 2022) .

In this study, we seek to untangle the relationship between two EBVs: forest structure diversity metrics and yearly summaries of forest productivity. To accomplish this, we assess this relationship using path analysis to assess the direct and indirect (as mediated by more complex forest structural diversity metrics) effects of commonly collected forest structural metrics (canopy height and canopy cover) on yearly productivity summaries. Doing so will in turn assess their utility as complementary EBVs. We ran this analysis separately across four forested land covers and the forested ecosystems of British Columbia, Canada.

## 2. Methods

### *2.1. Study Area*

British Columbia is the westernmost province of Canada, and is home to a variety of terrestrial ecosystems (Pojar et al., 1987). Approximately 64% of the province is forested (BC Ministry of Forests, 2003). There is a large amount of ecosystem variation in the province, with large climate and topographic gradients. The Biogeoclimatic Ecosystem Classification (BEC) system identifies 16 zones based on the dominant tree species and the ecosystems general climate. These zones can be further split into subzones, variants, and phases based on microclimate, precipitation, and topography.

### *2.2. Data*

### *2.3. Sampling*

### *2.4. Analysis*

## 3. Results

## 4. Discussion

## 5. Conclusion

## References


Ali, A., 2019. Forest stand structure and functioning: Current knowledge and future challenges. Ecological Indicators 98, 665–677. URL: https://gateway.webofknowledge.com/gateway/Gateway.cgi?GWVersion=2&SrcAuth=DOISource&SrcApp=WOS&KeyAID=10.1016%2Fj.ecolind.2018.11.017&DestApp=DOI&SrcAppSID=8ErhQvgXXQBtHJO9AGH&SrcJTitle=ECOLOGICAL+INDICATORS&DestDOIRegistrantName=Elsevier, doi:10.1016/j.ecolind.2018.11.017. place: Amsterdam Publisher: Elsevier WOS:000464891100067.

Andrew, M.E., Wulder, M.A., Coops, N.C., Baillargeon, G., 2012. Beta-diversity gradients of butterflies along productivity axes. Global Ecology and Biogeography 21, 352–364. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1466-8238.2011.00676.x, doi:10.1111/j.1466-8238.2011.00676.x. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1466-8238.2011.00676.x.

BC Ministry of Forests, 2003. British Columbia's Forests and their Management. Technical Report. URL: https://www.for.gov.bc.ca/hfd/pubs/docs/mr/mr113/forests.htm.

Bergen, K.M., Goetz, S.J., Dubayah, R.O., Henebry, G.M., Hunsaker, C.T., Imhoff, M.L., Nelson, R.F., Parker, G.G., Radeloff, V.C., 2009. Remote sensing of vegetation 3-d structure for biodiversity and habitat: Review and implications for lidar and radar spaceborne missions. Journal of Geophysical Research-Biogeosciences 114, G00E06. URL: https://www.webofscience.com/api/gateway?GWVersion=2&SrcAuth=DOISource&SrcApp=WOS&KeyAID=10.1029%2F2008JG000883&DestApp=DOI&SrcAppSID=USW2EC0FB0f86g21rqa8mTRWHZ2vU&SrcJTitle=JOURNAL+OF+GEOPHYSICAL+RESEARCH-BIOGEOSCIENCES&DestDOIRegistrantName=American+Geophysical+Union, doi:10.1029/2008JG000883. place: Washington Publisher: Amer Geophysical Union WOS:000273047000001.

Bojinski, S., Verstraete, M., Peterson, T.C., Richter, C., Simmons, A., Zemp, M., 2014. The concept of essential climate variables in support of climate research, applications, and policy. Bulletin of the American Meteorological Society 95, 1431–1443. URL: https://journals.ametsoc.org/view/journals/bams/95/9/bams-d-13-00047.1.xml, doi:10.1175/BAMS-D-13-00047.1.

Coops, N.C., Bolton, D.K., Hobi, M.L., Radeloff, V.C., 2019. Untangling multiple species richness hypothesis globally using remote sensing habitat indices. ECOLOGICAL INDICATORS 107. doi:10.1016/j.ecolind.2019.105567. tex.article-number: 105567 tex.eissn: 1872-7034 tex.orcid-numbers: Radeloff, Volker C/0000-0001-9004-221X Hobi, Martina/0000-0003-3537-9738 tex.researcherid-numbers: Radeloff, Volker C/B-6124-2016 tex.unique-id: WOS:000490757500029.

Coops, N.C., Tompalski, P., Goodbody, T.R.H., Queinnec, M., Luther, J.E., Bolton, D.K., White, J.C., Wulder, M.A., van Lier, O.R., Hermosilla, T., 2021. Modelling lidar-derived estimates of forest attributes over space and time: A review of approaches and future trends. Remote Sensing of Environment 260, 112477. URL: https://www.sciencedirect.com/science/article/pii/S0034425721001954, doi:10.1016/j.rse.2021.112477.

Currie, D.J., Mittelbach, G.G., Cornell, H.V., Field, R., Guégan, J.F., Hawkins, B.A., Kaufman, D.M., Kerr, J.T., Oberdorff, T., O'Brien, E., Turner, J.R.G., 2004. Predictions and tests of climate-based hypotheses of broad-scale variation in taxonomic richness. Ecology Letters 7, 1121–1134. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1461-0248.2004.00671.x, doi:10.1111/j.1461-0248.2004.00671.x. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1461-0248.2004.00671.x.

Davies, A.B., Asner, G.P., 2014. Advances in animal ecology from 3d-lidar ecosystem mapping. Trends in Ecology & Evolution 29, 681–691. URL: https://www.webofscience.com/api/gateway?GWVersion=2&SrcAuth=DOISource&SrcApp=WOS&KeyAID=10.1016%2Fj.tree.2014.10.005&DestApp=DOI&SrcAppSID=USW2EC0FB0f86g21rqa8mTRWHZ2vU&SrcJTitle=TRENDS+IN+ECOLOGY+%26+EVOLUTION&DestDOIRegistrantName=Elsevier, doi:10.1016/j.tree.2014.10.005.

Fernández, N., Ferrier, S., Navarro, L.M., Pereira, H.M., 2020. Essential Biodiversity Variables: Integrating In-Situ Observations and Remote Sensing Through Modeling. Springer International Publishing, Cham. chapter 18. pp. 485–501. URL: https://doi.org/10.1007/978-3-030-33157-3_18, doi:10.1007/978-3-030-33157-3_18.

Gao, T., Hedblom, M., Emilsson, T., Nielsen, A.B., 2014. The role of forest stand structure as biodiversity indicator. Forest Ecology and Management 330, 82–93. URL: https://www.sciencedirect.com/science/article/pii/S0378112714004241, doi:10.1016/j.foreco.2014.07.007.

Goetz, S., Steinberg, D., Dubayah, R., Blair, B., 2007. Laser remote sensing of canopy habitat heterogeneity as a predictor of bird species richness in an eastern temperate forest, usa. Remote Sensing of Environment 108, 254–263. doi:10.1016/j.rse.2006.11.016.

Guo, X., Coops, N.C., Tompalski, P., Nielsen, S.E., Bater, C.W., John Stadt, J., 2017. Regional mapping of vegetation structure for biodiversity monitoring using airborne lidar data. Ecological Informatics 38, 50–61. URL: https://www.sciencedirect.com/science/article/pii/S1574954116300905, doi:10.1016/j.ecoinf.2017.01.005.

Huete, A., Didan, K., Miura, T., Rodriguez, E.P., Gao, X., Ferreira, L.G., 2002. Overview of the radiometric and biophysical performance of the modis vegetation indices. Remote Sensing of Environment 83, 195–213. URL: https://gateway.webofknowledge.com/gateway/Gateway.cgi?GWVersion=2&SrcAuth=DOISource&SrcApp=WOS&KeyAID=10.1016%2FS0034-4257%2802%2900096-2&DestApp=DOI&SrcAppSID=6ABQuYtmtvvjzqEmPms&SrcJTitle=REMOTE+SENSING+OF+ENVIRONMENT&DestDOIRegistrantName=Elsevier, doi:10.1016/S0034-4257(02)00096-2. place: New York Publisher: Elsevier Science Inc WOS:000179160200014.

Knyazikhin, Y., Martonchik, J.V., Myneni, R.B., Diner, D.J., Running, S.W., 1998. Synergistic algorithm for estimating vegetation canopy leaf area index and fraction of absorbed photosynthetically active radiation from modis and misr data. Journal of Geophysical Research: Atmospheres 103, 32257–32275. URL: https://onlinelibrary.wiley.com/doi/abs/10.

1029/98JD02462, doi:10.1029/98JD02462. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/98JD02462.

Ma, Q., Su, Y., Hu, T., Jiang, L., Mi, X., Lin, L., Cao, M., Wang, X., Lin, F., Wang, B., Sun, Z., Wu, J., Ma, K., Guo, Q., 2022. The coordinated impact of forest internal structural complexity and tree species diversity on forest productivity across forest biomes. Fundamental Research URL: https://www.sciencedirect.com/science/article/pii/S2667325822004162, doi:10.1016/j.fmre.2022.10.005.

Macarthur, R., Macarthur, J., 1961. On bird species-diversity. Ecology 42, 594–598. URL: https://www.webofscience.com/api/gateway?GWVersion=2&SrcAuth=DOISource&SrcApp=WOS&KeyAID=10.2307%2F1932254&DestApp=DOI&SrcAppSID=USW2EC0FB0f86g21rqa8mTRWHZ2vU&SrcJTitle=ECOLOGY&DestDOIRegistrantName=JSTOR, doi:10.2307/1932254.

Matasci, G., Hermosilla, T., Wulder, M.A., White, J.C., Coops, N.C., Hobart, G.W., Bolton, D.K., Tompalski, P., Bater, C.W., 2018. Three decades of forest structural dynamics over canada's forested ecosystems using landsat time-series and lidar plots. Remote Sensing of Environment 216, 697–714. URL: https://linkinghub.elsevier.com/retrieve/pii/S0034425718303572, doi:10.1016/j.rse.2018.07.024.

McGill, B.J., Dornelas, M., Gotelli, N.J., Magurran, A.E., 2015. Fifteen forms of biodiversity trend in the anthropocene. Trends in Ecology & Evolution 30, 104–113. URL: https://www.sciencedirect.com/science/article/pii/S0169534714002456, doi:10.1016/j.tree.2014.11.006.

Myneni, R.B., Williams, D.L., 1994. On the relationship between fapar and ndvi. Remote Sensing of Environment 49, 200–211. URL: https://www.sciencedirect.com/science/article/pii/0034425794900167, doi:10.1016/0034-4257(94)90016-7.

Nelson, R., Keller, C., Ratnaswamy, M., 2005. Locating and estimating the extent of delmarva fox squirrel habitat using an airborne lidar profiler. Remote Sensing of Environment 96, 292–301. URL: https://www.webofscience.com/api/gateway?GWVersion=2&SrcAuth=DOISource&SrcApp=WOS&KeyAID=10.1016%2Fj.rse.2005.02.012&DestApp=DOI&SrcAppSID=USW2EC0FB0f86g21rqa8mTRWHZ2vU&SrcJTitle=REMOTE+SENSING+OF+ENVIRONMENT&DestDOIRegistrantName=Elsevier, doi:10.1016/j.rse.2005.02.012.

Pereira, H.M., Ferrier, S., Walters, M., Geller, G.N., Jongman, R.H.G., Scholes, R.J., Bruford, M.W., Brummitt, N., Butchart, S.H.M., Cardoso, A.C., Coops, N.C., Dulloo, E., Faith, D.P., Freyhof, J., Gregory, R.D., Heip, C., Hoft, R., Hurtt, G., Jetz, W., Karp, D.S., McGeoch, M.A., Obura, D., Onoda, Y., Pettorelli, N., Reyers, B., Sayre, R., Scharlemann, J.P.W., Stuart, S.N., Turak, E., Walpole, M., Wegmann, M., 2013. Essential biodiversity variables. Science 339, 277–278. URL: https://www.sciencemag.org/lookup/doi/10.1126/science.1229931, doi:10.1126/science.1229931.

Pojar, J., Klinka, K., Meidinger, D., 1987. Biogeoclimatic ecosystem classification in british columbia. Forest Ecology and Management 22, 119–154. URL: https://linkinghub.elsevier.com/retrieve/pii/0378112787901009, doi:10.1016/0378-1127(87)90100-9.

Radeloff, V.C., Dubinin, M., Coops, N.C., Allen, A.M., Brooks, T.M., Clayton, M.K., Costa, G.C., Graham, C.H., Helmers, D.P., Ives, A.R., Kolesov, D., Pidgeon, A.M., Rapacciuolo, G., Razenkova, E., Suttidate, N., Young, B.E., Zhu, L., Hobi, M.L., 2019. The dynamic habitat indices (dhis) from modis and global biodiversity. Remote Sensing of Environment 222, 204–214. URL: https://www.sciencedirect.com/science/article/pii/S0034425718305625, doi:10.1016/j.rse.2018.12.009.

Razenkova, E., Radeloff, V.C., Dubinin, M., Bragina, E.V., Allen, A.M., Clayton, M.K., Pidgeon, A.M., Baskin, L.M., Coops, N.C., Hobi, M.L., 2020. Vegetation productivity summarized by the dynamic habitat indices explains broad-scale patterns of moose abundance across russia. Scientific Reports 10, 836. URL: https://www.nature.com/articles/s41598-019-57308-8, doi:10.1038/s41598-019-57308-8. number: 1 Publisher: Nature Publishing Group.

Skidmore, A.K., Coops, N.C., Neinavaz, E., Ali, A., Schaepman, M.E., Paganini, M., Kissling, W.D., Vihervaara, P., Darvishzadeh, R., Feilhauer, H., Fernandez, M., Fernández, N., Gorelick, N., Geijzendorffer, I., Heiden, U., Heurich, M., Hobern, D., Holzwarth, S., Muller-Karger, F.E., Van De Kerchove, R., Lausch, A., Leitão, P.J., Lock, M.C., Mücher, C.A., O'Connor, B., Rocchini, D., Turner, W., Vis, J.K., Wang, T., Wegmann, M., Wingate, V., 2021. Priority list of biodiversity metrics to observe from space. Nature Ecology & Evolution URL: http://www.nature.com/articles/s41559-021-01451-x, doi:10.1038/s41559-021-01451-x.

Thomas, C.D., Cameron, A., Green, R.E., Bakkenes, M., Beaumont, L.J., Collingham, Y.C., Erasmus, B.F.N., de Siqueira, M.F., Grainger, A., Hannah, L., Hughes, L., Huntley, B., van Jaarsveld, A.S., Midgley, G.F., Miles, L., Ortega-Huerta, M.A., Peterson, A.T., Phillips, O.L., Williams, S.E., 2004. Extinction risk from climate change. Nature 427, 5.

Urban, M.C., 2015. Accelerating extinction risk from climate change. Science 348, 571–573. URL: https://www.science.org/doi/10.1126/science.aaa4984, doi:10.1126/science.aaa4984.

Williams, S.E., Middleton, J., 2008. Climatic seasonality, resource bottlenecks, and abundance of rainforest birds: implications for global climate change. Diversity and Distributions 14, 69–77. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1472-4642.2007.00418.x, doi:10.1111/j.1472-4642.2007.00418.x. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1472-4642.2007.00418.x.

Wright, D.H., 1983. Species-energy theory: An extension of species-area theory. Oikos 41, 496–506. URL: https://www.jstor.org/stable/3544109, doi:10.2307/3544109. publisher: [Nordic Society Oikos, Wiley].