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Review of the doctoral dissertation of M.Sc. Umberto Grande entitled: "Goal functions and the assessment of natural capital and ecosystem services"

Formal analysis of the dissertation

The doctoral dissertation was prepared in the Department of Geobotany and Landscape Planning at Nicolaus Copernicus University in Toruń, in cooperation with the UNESCO Chair "Environment, Resources and Sustainable Development" at Parthenope University of Naples, Italy. The work was supervised by dr hab. Agnieszka Piernik, prof. NCU; prof. Pier Paolo Franzese; and associate prof. Elvira Buonocore. The dissertation includes 112 pages of core text and is organized into six chapters: Introduction, Methods, Results (including one publication and two manuscripts), Discussion, Conclusions and Bibliography. An additional seven pages contain acknowledgements and supplementary materials.

The thesis is built upon three closely linked research papers:

1. **Grande U.,** Piernik A., Nienartowicz A., Buonocore E., Franzese P. 2023: Measuring natural capital value and ecological complexity of lake ecosystems, *Ecological Modelling*, vol. 482, 110401, p. 1-9, DOI:10.1016/j.ecolmodel.2023.110401.
2. **Grande U**., Buonocore E., Fiorentino F., Franzese P.P, Lauria V., Piernik A., Sabatella E., Scannella D, S. Vitale S., G. Garofalo G. Applying goal functions for natural capital stock change assessments in marine ecosystems. Manuscript. Target journal: *Conservation Biology* (planned submission awaiting coauthors' approval).
3. **Grande U.,** Husein K., Nardella L., Kamiński D., Buonocore E., Franzese P.P., Piernik A. Assessing forest ecosystem assets and services based on an international statistical standard. Manuscript. Target journal: *Ecological Indicators* (under review).

Assessment of the candidate's ability to carry out independent scientific research

M.Sc. Umberto Grande is the first author of all three articles and played one of the leading role in every stage of the studies: planning, database collection, software development, statistical analysis, interpretation and co-writing the first drafts as well as versions after reviews. The studies cover freshwater, marine and forest ecosystems, so the candidate had to choose or build different modelling tools and follow various statistical standards. He also linked ecological results with economic evaluation frameworks such as SEEA-EA, proving that he can move confidently across disciplines. The candidate worked with senior scientists from several institutions and countries, coordinated analysis, merged complex data sets and guided one manuscript through peer review. These tasks required strong management skills and clear communication. Taking all this evidence together, it is clear that M.Sc. Umberto Grande can design and conduct original research projects on his own. He therefore fully fulfils the requirement of being able to conduct independent scientific work in the field of biological sciences, and he meets the standards expected for the PhD degree.

Assessment of the doctoral dissertation with regard to the candidate's presentation of general theoretical knowledge in the relevant discipline

The doctoral dissertation explores the potential of thermodynamic Goal Functions: emergy and eco-exergy, and the United Nations SEEA-EA ecosystem-accounting framework to enrich understanding of natural-capital stocks and ecosystem-service across diverse aquatic and forest ecosystems. The author test how efficiently these biophysical indicators capture spatial and temporal variability in ecosystems that are of the highest importance for biodiversity conservation, thereby combining a deeper theoretical insight with an applied concern for sustainable development. The introductory chapters and discussions in the dissertation guide the reader through the concept of Goal Functions, elucidating their grouping into biotic, network and thermodynamic categories and clarifying why emergy (the cumulative 'work of nature') and eco-exergy (the organisation level of biomass) can complement rather than compete in evaluation processes. The synthesis connects global challenges to the local scale and includes results from multiple case studies to build coherent ecological concept.

The candidate's theoretical background is also evident in the detailed presentation of ecological processes – understood in terms of systems ecology – associated with the specific ecosystem types studied in the dissertation. Elements of ecosystem metabolism and the structure of trophic relationships are clearly characterized, which is essential when assessing natural capital and ecosystem services. Theoretical competence is further demonstrated by the ability to represent and apply these relationships in modelling. A good example is the conceptual diagram of the lake system presented in Article No. 1, Fig. 3. Building on this conceptual platform, the dissertation undertakes a series of empirically coherent tasks. By demonstrating that thermodynamic indicators respond sensitively to e.g. nutrient enrichment, aquaculture effluents and storm damage, the author shows how a multi-method approach can inform decision-makers to emergent ecological tipping points before they transform into financial and social costs.

In conclusion, dissertation fully satisfies the criterion of demonstrating general theoretical background in the relevant discipline. The candidate not only displays complex ecological concepts but also joins them creatively to generate original insights of clear applied value. In my opinion, the doctoral dissertation presented by M.Sc. Umberto Grande fully meets the requirement of demonstrating broad theoretical knowledge in the discipline of biological sciences and meets the expectations for the doctoral degree.

Assessment of the doctoral dissertation with regard to the resolve of an original scientific problem and the originality of the practical application of the candidate's research findings

The dissertation fills a clear scientific gap by integrating thermodynamic Goal Functions – emergy and eco-exergy – with the UN's SEEA-EA framework, linking ecosystem understanding with management-relevant metrics. While usually using separately in the literature, these approaches are here unified into a quantitative solution, and presenting how ecosystem values can be understood in decision-making. This concept was tested across three case studies.

The first (Article No. 1) was conducted is a set of nearby located forest lakes in the Northern Poland – Czarne (oligotrophic), Zmarle (mesotrophic) and Laska (eutrophic) – where emergy

and eco-exergy as well as eco-exergy/emergy ratio were calculated. In this study, the emergy method was used for assessing the biophysical value of natural capital stocks. The maximum value among the turnover time of the different biomass groups (3 years) was chosen considering that all groups are co-products of the total emergy invested. The total eco-exergy of an ecosystem is computed as the sum of the eco-exergy values calculated for all the organisms living in lakes. In the paper eco-exergy was measures with using ß-values, which estimates content of organism's genes in the ecosystem. However, in the method section, I didn't find the sources of information on list of taxa noted in the studied lakes. A brief clarification would help indicate the source of the lakes' taxonomic data – or, if the authors collected the samples themselves, add a short note on the sampling procedure.

The total emergy and the emergy density values resulted higher for the Laska lake compared to the other investigated lakes. Hence, the highest emergy investment for the generation of natural capital stocks resulted in this eutrophic reservoir, mainly due to the high convergence of nitrogen and phosphorus flows. The highest value of total eco-exergy and eco-exergy density also resulted for the Laska lake. These outcomes are mainly due to the high biomass value of macrophytes and aquatic birds. Furthermore, the eco-exergy/emergy ratio was used to assess the lakes' efficiency in transforming natural inputs flows into ecosystem components. The results were higher for the Zmarle lake compared to Czarne and Laska lakes. Therefore, despite the highest eco-exergy value of natural capital calculated for the Laska lake, the results highlighted the better efficiency of the Zmarle lake in maintaining and developing ecosystem structures and organization. In fact, the large amount of nutrients coming from the nearby salmon farm outweighed the carrying capacity of the Laska lake, resulting in a lower efficiency of the ecosystem.

The emergy and eco-exergy calculations have been previously applied to investigate natural ecosystems but there are no research specifically assessing the value of biotic natural capital stocks in freshwater lake ecosystems by jointly using both methods. Therefore, presented framework can be a first point for further analysis by other authors. The results clearly show that lakes of different trophic states differ in natural capital and functioning. While valid, it is important to recognize that trophic status can also reflects natural variation, not necessarily ecological degradation. Indicators

like emergy or eco-exergy can therefore be also interpreted within lake-type context, and comparisons can be made between lakes of similar typology to avoid underestimating naturally oligotrophic systems.

A second (Article No. 2) manuscript concerns the Strait of Sicily (Italy), a biodiversity hotspot under fishing pressure, to examine fifteen years of trawl survey data. Hypothesis assumes that ecosystem Natural Capital can be affected by human activity and environmental parameters and can change over time. By compiling eco-exergy with the Shannon diversity index and spatial hotspot analysis, authors identified zones where lower system complexity corresponds to thermal stress and demonstrates that used thermodynamic indicators can warn managers of emergent ecological risk before it will be visible in diversity statistics.

In the analysis authors investigated trends in time for NC and for potential drivers of NC change. The time series were standardized using a linear regression model with a indicator variable for the season, a factor controlling for the seasonal effect. This effectively standardized data allowing a more consistent analysis. Most of the analysis were done in R environment. However, in methods description, R packages names used in analysis should be introduce as well as property citations. Providing this information is standard practice and will strengthen the transparency and reproducibility of the work. For spatial analysis, georeferenced data on eco-exergy and diversity indices were used to create annual distribution maps through inverse distance-weighted (IDW) deterministic interpolation. In addition, hotspot analysis, a technique that identifies statistically significant spatial clusters of high values (hot spots) and low values (cold spots) were used. Finally, annual hotspots of eco-exergy and diversity were overlaid for each of the three defined 5-year time intervals.

Results highlight a significant decline in NC stocks of the benthic component of the marine system over the studied period, which occurred specifically in the slope zones. In contrast, no significant decline was observed on the shelf. Regarding the Shannon index, the analysis did not reveal any significant trends. These findings revealed that eco-exergy can provide earlier warnings on alterations to ecosystem health and functioning compared to the biodiversity indexes. Integrating the eco-exergy and Shannon indexes allowed authors to identify two persistent hotspots

within the system characterized by high values for both indices. Ecosystems with high NC and diversity of the benthic fishery resources are areas of high ecological value and crucial for providing ecological services. This result can provide helpful scientific information to policymakers in support of strategic conservation efforts and effective, sustainable fishery management. This is the first study that aims to implement a multi-methodological framework integrating the use of thermodynamic GF, diversity index, and spatial and hotspot analysis to assess the spatiotemporal trend of NC stocks.

The third (Article No. 3) case study adapts SEEA-EA to Poland's Tuchola Forest UNESCO-MAB Reserve – apparently the framework's first deployment in any Man-and-Biosphere site. The study focused on two main aspects: (1) assessing the Tuchola Forests ability to improve air quality and (2) tracking changes in forest ecosystem services after natural disturbances. A decline in air purification capacity and ES supply was expected following the 2017 hurricane. The study used abiotic state indicators – specifically air pollutant concentrations of PM10, PM2.5, NO_2, and O_3, selected based on ecosystem type and data availability. The forward step involved the Leaf Area Index (LAI) as a vegetation state indicator, essential for estimating trees' capacity to remove particulate matter. The removal capacity of PM10, PM2.5, NO_2, and O_3 was assessed for forest conditions before and after the hurricane. Results shown that coniferous forests in the studied area decreased by 4.75%, while transitional woodland shrubs increased by 5.09%, reflecting post-hurricane successional dynamics. This shift indicates natural regeneration following tree-stands damage. Conifer stands maintained stable LAI throughout the year, while broadleaf forests dropped in winter. Pollutant removal efficiency (PM10, PM2.5, NO_2, O_3) was analysed by forest type and season. Although deciduous trees were more efficient during the growing season, conifers provided greater overall annual air filtration due to their wider coverage. The economic value of this service was highest for conifers (773.9 M euro), with a total annual value of 791 M euro. The hurricane caused a 7.4 M euro loss in ES value, indicating how climate-induced disturbances can reduce ecosystem capacity and introduce risks to human health through diminished air quality benefits.

The analysis puts forward the hypothesis that ecosystem service supply can be influenced not only by anthropogenic pressures but also by natural disturbances such as storms. While this is analytically correct – especially within policy-oriented frameworks – it is important to recognize that such disturbances are also natural components of ecosystem dynamics. Events like storms, wildfires, or insect outbreaks can contribute to resilience, habitat diversification, and ecological renewal. Acknowledging this dual perspective – distinguishing between temporary losses from a human-benefit viewpoint and potential long-term ecological gains – would provide a more balanced and ecologically grounded interpretation of natural capital dynamics in forest ecosystems.

Presented studies demonstrate a coherent pathway from original concept to applicable solutions. Consequently, the dissertation includes both, from the originality with which it resolves scientific problem – integrating ecological and socio-economic perspectives, to solutions that forest, lake and marine managers can adopt. The way in which the research was planned, conducted using modern approaches, and the results analysed, forms the basis for my **high evaluation of M.Sc. Umberto Grande doctoral dissertation** – both in terms of addressing an scientific problem and in proposing an innovative application of the results of his own research.

Final recommendation

Considering the above remarks and the **positive evaluation of M.Sc. Umberto Grande's doctoral dissertation** in all assessed aspects, I confirm that the thesis fulfils the requirements laid down in Article 187 of the Act of 20 July 2018 on Higher Education and Science in Poland (Art. 187 Ustawy z dnia 20 lipca 2018 r. Prawo o szkolnictwie wyższym i nauce, Dz. U. 2023.742 ze zm.). On this basis, **I respectfully recommend** that the Council of the Discipline of Biological Sciences at Nicolaus Copernicus University in Toruń (Rada Dyscypliny Nauki Biologiczne Uniwersytetu Mikołaja Kopernika w Toruniu) admit M.Sc. Umberto Grande to the next stages of the doctoral procedure.