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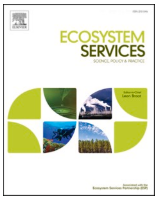

Short Communication

Legitimacy and limitations of valuing the oxygen production of ecosystems

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ABSTRACT

Oxygen production is an ecosystem service essential to life on Earth. However how it should be valued is controversial and depends on several factors. Here, we commented on how valuation might be applicable to the stock or flow of oxygen, whether additional oxygen produced at the micro or macro scale provides additional human wellbeing, and whether double counting may occur if oxygen production and carbon sequestration are both valued independently and added. We concluded that the flow of oxygen produced by ecosystems should be valued when: (1) high levels of atmospheric oxygen at specific micro-scale areas (e.g., a park) provides additional benefits to local human health and additional attraction to tourists; (2) micro-scale aquatic oxygen production (e.g., in a pond or aquafarm) avoids potential loss of aquatic products; and (3) macro-scale aquatic oxygen production (e.g., in global oceans) maintains marine contributions to humans (e.g., fishery resources). However, whether macro-scale atmospheric oxygen production should be valued is uncertian, because the effects of declining global atmospheric oxygen, especially in the short term, remain unclear. This needs further research. We also concluded that the values of oxygen production and carbon sequestration can be aggregated without double counting, given that the values are not duplicated in multiple ecosystem service categories. For example, oxygen production is best considered as contributing to gas regulation while carbon sequestration contributes to climate regulation. But one should not count and add both carbon sequestration and oxygen production as contributing to both gas and climate regulation. Techniques for valuing oxygen production may include the willingness to pay for additional health benefits of breathing extra high levels of atmospheric oxygen, the market price of industrial oxygen, the travel cost to natural 'oxygen bars', the avoided cost of losing aquatic resources, and the replacement cost of using artificial techniques to produce oxygen.

1. Introduction

Ecosystems produce oxygen through photosynthesis and absorb oxygen during respiration. The net production of oxygen is a crucial component of the Earth's life-supporting ecosystems, underpinning the wellbeing of people and the planet. Hence, oxygen production is widely considered as an ecosystem service (ES) – one of the benefits humans receive from ecosystem functions, processes, or characteristics (CBD 2020b; Costanza et al. 1997; FAO 2022; Millennium Ecosystem Assessment 2005; TEEB 2019). ES valuation in monetary units has received increasing attention worldwide to link environmental changes with socioeconomic benefits, visualise nature's contributions to people, complement other arguments for the conservation and restoration of nature, and measure development and human wellbeing more comprehensively (Chen et al. 2022; Costanza et al. 2014; IPBES 2019a; United Nations et al. 2021). However, how and when oxygen production should be valued is controversial. This paper discusses existing concerns and makes suggestions on this issue.

2. Concerns about stocks and flows

The ES concept is about flows (the quantity measured over a period of, or per unit of, time), rather than stocks (the existing quantity measured at a certain point in time, which may have accumulated in the past) which are called natural capital (Costanza et al. 2014; United Nations et al. 2021). It is difficult to assess the value of the total stock of oxygen, because if the current oxygen stock is fully depleted from Earth, even for a day, humans and many other species could not survive. But that is true for many other stocks in the ecosystem, including water, nitrogen, carbon, etc. It is also true that oxygen was not always part of the Earth's atmosphere and anerobic metabolism is possible and occurs at several locations on the current Earth where oxygen is limited.

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Table 1
A subset of peer-reviewed macro-scale ES valuation studies in/excluding the oxygen production in the last 10 years.

Scales	Integrating oxygen production	Excluding oxygen production
National	Chen (2021); China National Environmental Management Standadisation Technical Commission (2020)	Arowolo et al. (2018); Kubiszewski et al. (2013)
International	Jiang et al. (2021); Newton et al. (2018)	Costanza et al. (2014); de Groot et al. (2012); Kubiszewski et al. (2017); Taye et al. (2021); United Nations et al. (2021)

ES valuation is about valuing the flows of oxygen production, namely, the additional amount of oxygen produced within a certain period, or per unit of time (e.g., one year). For example, provided that the additional oxygen produced in 2022 is × tonnes and the total oxygen stock at the end of 2022 is y tonnes in a certain region, ES valuation is about value assessment of the × (rather than the y) tonnes of oxygen.

3. Concerns about additional contributions to human wellbeing

Determining if the flow of an ES should be valued should consider whether an additional amount of the ES improves human wellbeing and the scale at which the valuation is conducted (Costanza et al. 1997; Costanza et al. 2017; de Groot et al. 2002). It is difficult to observe how change in oxygen production at the micro scale (e.g., a local park) may affect human wellbeing at the macro scale (e.g., global, continental, national). For example, the contributions of oxygen production from a hectare of forest to global air quality is unlikely to be observed.

Contributions of oxygen produced by micro-level ecosystems to micro-level human wellbeing can be observed and valued at least in the following cases. Compared to average built-up areas, breathing at natural areas with higher atmospheric content of oxygen may bring humans more health benefits, including deterring inhalation of fine particulates, regulating oxygen concentration and serotonin in blood and brain, boosting the immune system, improving neuropsychological performance and sleep quality, and alleviating mood disorders and depression (Bowers et al. 2018; Jiang et al. 2018; Mao et al. 2012; Pino and La Ragione 2013; Zhu et al. 2021). Some well-preserved places (e.g., Gili Iyang Island in Indonesia, Mount Emei and Panda Reserves in China) with extra atmospheric content of oxygen are advertised as natural 'oxygen bars' to attract visitors and boost tourism revenue (Li and Huang 2018; Sannigrahi et al. 2019; Wang et al. 2022). This demonstrates that the difference in the levels of oxygen between the well-preserved areas and other average built-up areas is valuable to improvement of human wellbeing. Moreover, if oxygen content in either fresh or marine water declines below a minimum oxygen level (often because of plastic debris and organic matter discharged, introduction of invasive plants that over-consume oxygen and shade endemic plants from light, fossil fuel use, or fertilisers' that stimulate growth of algae that deplete oxygen when they die and decompose), the water will become a 'dead zone' unavailable to most aerobic aquatic life (e.g., fish, coral) (Altieri et al. 2017; CBD 2020a; Müller et al. 2015; TEEB 2009). If aerobic aquatic life cannot escape from dead zones in micro-scale water (e.g., a closed pond or aquafarm), they will choke slowly and die, causing economic damage.

Whether ES valuation at the macro scale should integrate oxygen production has not reached a consensus (Table 1). The Earth's atmospheric oxygen level increased dramatically after the "Great Oxidation Event" (approximately 2.45 – 2.32 billion years ago), especially from 470 million years ago when land plants emerged (Kasting 2013; Krause et al. 2018; Lenton et al. 2016; Lyons et al. 2014). After the long-term accumulation (Fig. 1), oxygen currently accounts for roughly 21 % of the atmosphere by volume, being a relatively abundant resource for life on Earth. Based on the marginalist economic theory characterised by the diminishing marginal value (e.g., a candy lover receives lower utility from the 100th candy than the 1st candy), the value of the additional amount of oxygen produced by global ecosystems each year may be negligible and hence does not need to be assessed. This viewpoint could be correct provided that global oxygen was not declining, because producing additional oxygen in this case only means global oxygen would just remain abundant.

However, in fact, the mass of global oxygen is declining in both the atmosphere (Fig. 2) and especially marine water (Fig. 3), due to (1) reduced terrestrial oxygen production along with land degradation, (2) increasing fossil fuel combustion, (3) respiration growth of humans and livestock along with human population growth, (4) climate change and nutrients discharged into water, which together decrease oxygen

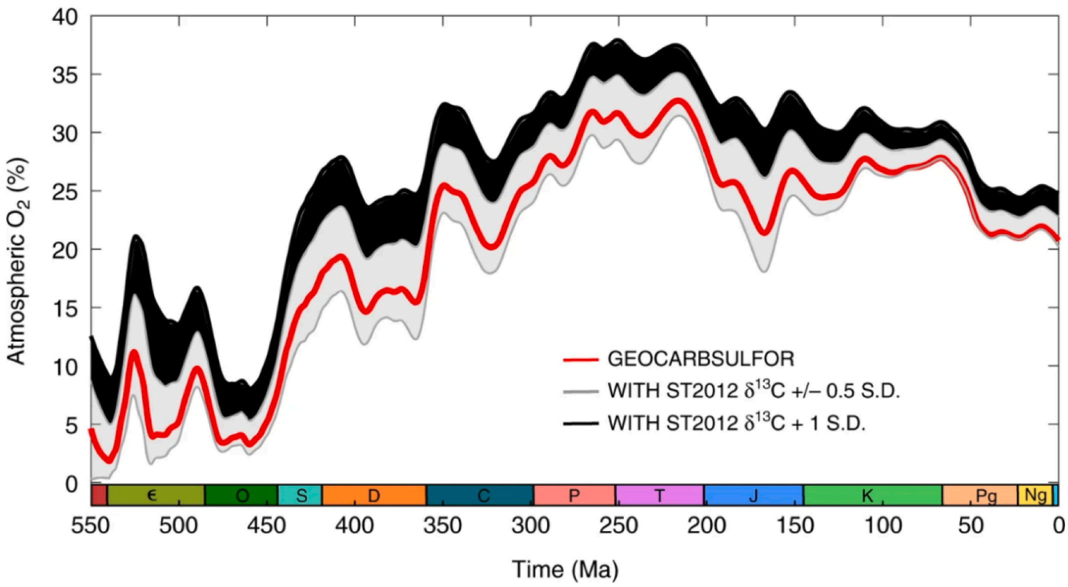

Fig. 1. Changes in proportion of oxygen in Earth's atmosphere.
Note: The red line is the GEOCARBSULFOR model, the grey envelope is generated by ± half a standard deviation change to the ocean–atmosphere δ13C record, and the black envelope is the + 1 standard deviation. "One Ma" means "one million years ago".
Source: (Krause et al. 2018).

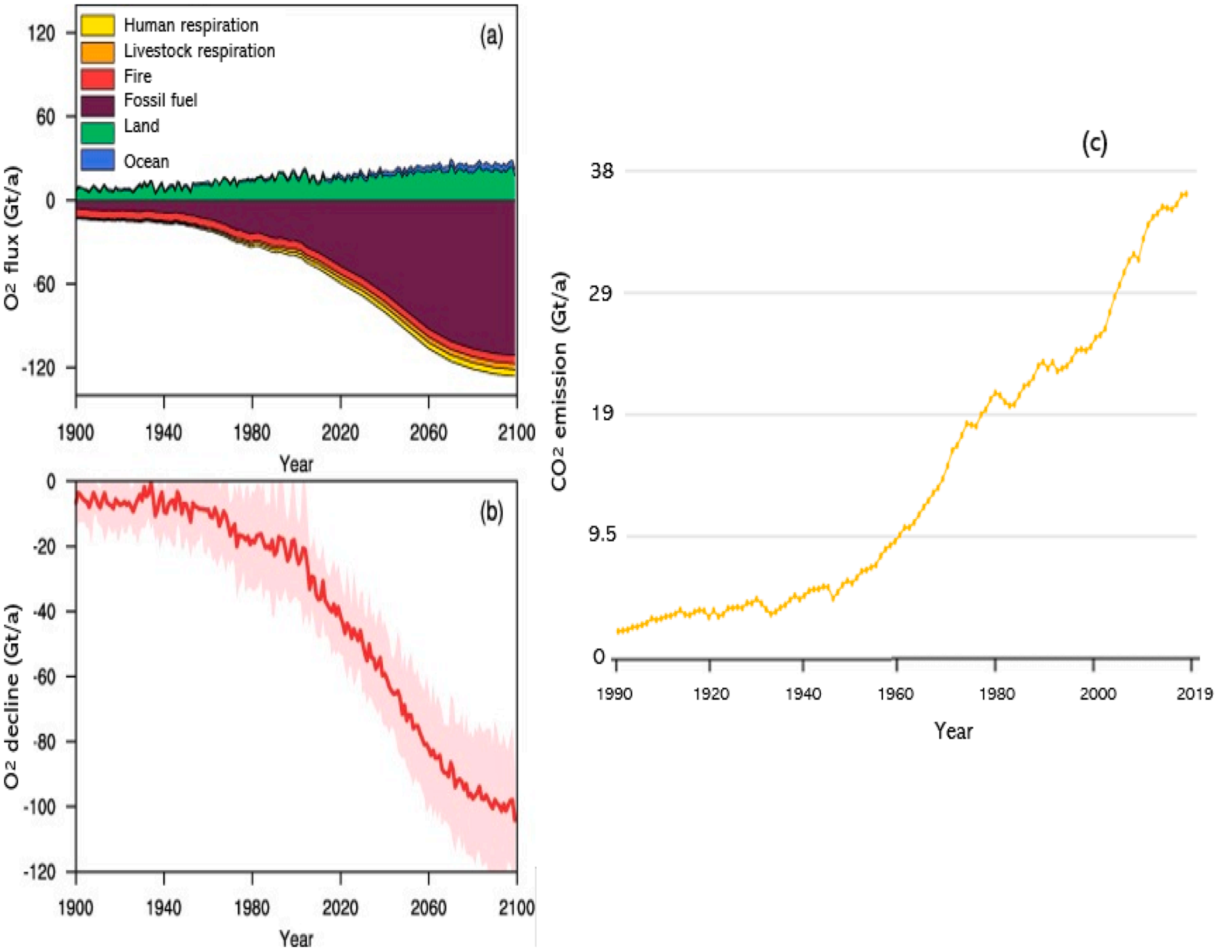

Fig. 2. Temporal variation of the global atmospheric oxygen and carbon dioxide from 1990. (a) Oxygen consuming and producing processes under the Representative Concentration Pathways (RCP) 8.5 scenario from 1900 to 2100. The shades below and above zero denote the processes that remove or produce oxygen, respectively. (b) Annual net atmospheric oxygen loss from 1900 to 2100 under the RCP8.5 scenario. (c) Annual carbon dioxide emission from 1900 to 2019. **Source**: (a) and (b) are from Huang et al. (2018). (c) is from World Resource Institute (2022). **Note**: CO_2 emission is also presented here, because fossil fuel burning is the major contributor to both oxygen decline and CO_2 emission, and oxygen decline is like the mirror image of CO_2 emission. "Gt/a" is "Gigatonne per annum", and a gigatonne is a billion tonnes.

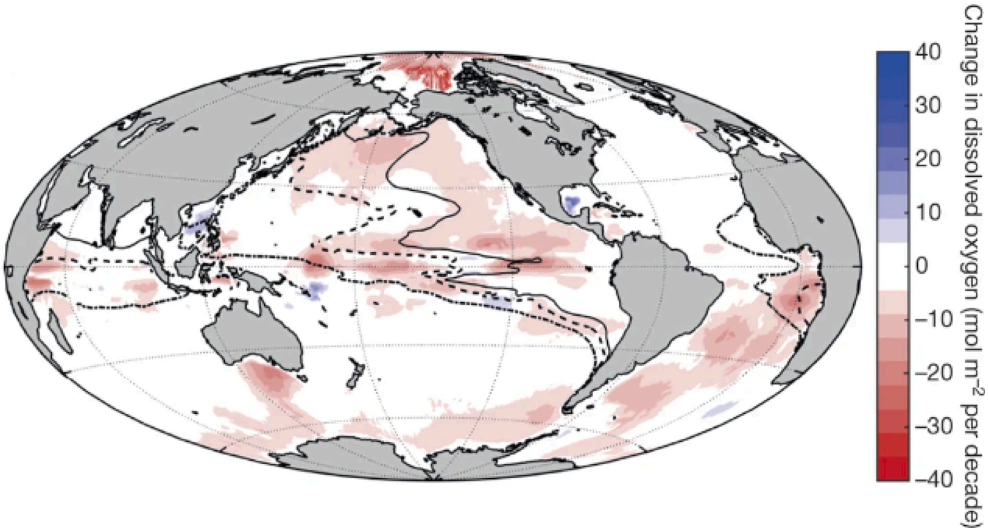

Fig. 3. Change in global marine dissolved oxygen per decade since 1960. **Source**: (Schmidtko et al. 2017).

solubility and oxygen resupply from the atmosphere but increase microbial respiration and metabolic oxygen demand in water, and (5) increasing solar fluxes that deoxygenate the atmosphere (Altieri and Gedan 2015; Breitburg et al. 2018; Huang et al. 2018; Liu et al. 2020; Ozaki and Reinhard 2021; Schmidtko et al. 2017).

Declining marine oxygen has increased dead zones exponentially since the 1960s, affecting a total global marine area of over 245,000 km^2 negatively (Diaz and Rosenberg 2008). This includes reduced marine ecosystem connectivity (as fish may not migrate through dead zones), biodiversity loss (e.g., loss of habitats; mortality of fish, crustacean, and coral reefs), alteration of the structure of food webs, marine food insecurity for humans, reduced recreation (e.g., loss of opportunities to see fish and live corals) of costal tourism, and loss of livelihoods of marine-dependent people (e.g., fishery workers) (Altieri and Diaz 2019; Altieri et al. 2017; Breitburg et al. 2018). Even if some marine species (e.g., fish) may escape from dead zones into oxygen-abundant water in the short term, continuous dead zone spreading will ultimately lead to ecosystem crisis and tremendous socioeconomic damage. Therefore, macro-level oxygen production in marine water is crucial to maintenance of marine ecosystem health and its contributions to human wellbeing, and hence should be valued.

The effects of declining atmospheric oxygen in the long term is foreseeable, including hypoxic cities during extremely calm weather, severely muted primary productivity, and the inability to achieve combustion, when oxygen is less than 19.5 %, 16 %, and 12 % of the atmosphere by volume, respectively (Belcher and McElwain 2008; Cole et al. 2022; Wei et al. 2021). However, the short-term consequences of declining oxygen level in the atmosphere, such as reduction from the current 20.95 % to 20.83 % by 2100 (Huang et al. 2018; Liu et al. 2020), are unclear. Therefore, there should be further research on the short-term implications of the changes in atmospheric oxygen production to ecological and socioeconomic systems.

4. Concerns about double counting

As oxygen production and carbon sequestration are the joint outcomes of photosynthesis, some researchers may be concerned about double counting of photosynthesis when carbon sequestration and oxygen production are both valued separately and aggregated (Xue and Tisdell 2001). However, this concern confuses ESs with ecological process and misunderstands double counting. Photosynthesis is an ecological process, rather than an ES. A single ecological process may produce multiple types of ESs (de Groot et al. 2002), and double counting does not mean valuing multiple ESs produced by a single ecological process. Instead, double counting means counting the value of an ES more than once and occurs when values of overlapping ESs are assessed separately and summed (Chen 2020; Fu et al. 2011; Hein et al. 2006). Oxygen production contributes to the quality of air in the atmosphere, water, or soil, whereas carbon sequestration regulates global warming and water acidity (IPBES 2019b; Maikhuri and Rao 2012; Millennium Ecosystem Assessment 2005; Renforth and Henderson 2017). Therefore, oxygen production and carbon sequestration provide separate, rather than overlapping, contributions to human wellbeing, and so can be valued separately and aggregated without necessarily being double counted (Chen 2021; Ouyang et al. 1999). The keyword here is “not necessarily”.

Oxygen production and carbon sequestration are both the proxies for both gas regulation (contribution to maintenance of healthy air, including the carbon/oxygen balance, maintenance of the ozone layer, removal of air-borne pollutants and bacteria) and climate regulation (regulation of temperature, precipitation and other biologically mediated climatic process, including carbon/oxygen balance, greenhouse gas absorption, rainfall and drought regulation) via net primary production (Costanza et al. 1997; de Groot et al. 2002; UNEP 2014; Wallace 2007). However, if oxygen production is counted in both gas and climate regulation and then aggregated, double counting occurs. Therefore, when valuing ESs, oxygen production should only be categorised into one or the other of climate and gas regulation.

Table 2
Potential techniques valuing oxygen.

Scales	Cases	Techniques of value of oxygen production
Micro-scale oxygen production’s effects on macro-scale human wellbeing	Difficult to observe	Not applicable
Micro-scale oxygen production’s effects on micro-scale human wellbeing	Extra high levels of atmospheric oxygen provides additional benefits to local human health	(1) Willingness to pay for additional health benefits of breathing extra high levels of atmospheric oxygen, either revealed in reality (e.g., a real-world hotel may have different prices for rooms with and without windows) or stated in hypothetical scenarios (e.g., if you are travelling, would you be willing to pay extra money for a hotel located in an area with higher atmospheric oxygen content than other hotels?) (2) Market price or cost of producing equal extra amount of industrial oxygen into the local atmosphere. “Extra amount” means the amount above the average atmospheric content.
	Extra high levels of atmospheric oxygen provides additional attraction to tourists	(1) Travel cost of those who travel to natural ‘oxygen bars’ (2) Market price or cost of producing equal extra amount of industrial oxygen into the local atmosphere
	Aquatic oxygen production (e.g., in a pond or aquafarm) avoids potential loss of aquatic products and resources	(1) Economic cost of potential loss of aquatic products and resources avoided by aquatic oxygen production (2) Cost of using artificial techniques to pump equal amount of oxygen into water to ensure target aquatic species live and grow
Macro-scale oxygen production’s effects on macro-scale human wellbeing	Macro-scale marine oxygen production maintains ecological and socioeconomic benefits of global oceans	As per above
	Macro-scale atmospheric oxygen production	Uncertain, because the effects of declining global atmospheric oxygen, especially in the short term, remain unclear

Moreover, misuse of valuation techniques, such as afforestation cost, may cause double counting. Afforestation cost is the cost of planting trees artificially to provide the equal type and quantity of an ES. Some studies valued carbon sequestration using the afforestation cost, valued oxygen production using the market price or cost of industrial oxygen, and then aggregated these two ESs’ values (Cai et al. 2020; Li and Gao 2016; Ninan and Inoue 2014; Zhao et al. 2004). In this context, the value of oxygen production is double counted, because newly planted trees not only sequester carbon but also produce oxygen, namely, the afforestation cost already includes both the costs of restoring carbon sequestration and oxygen production (Xue and Tisdell 2001). To avoid double counting, the values of oxygen production and other ESs should not be assessed based on the afforestation cost and then aggregated. However, there are other potential valuation techniques applicable to oxygen production in Section 5 below.

5. Potential valuation techniques applicable to oxygen production

Potential cases where oxygen is produced by ecosystems, as well as the relevant valuation techniques (where applicable), are summarised in Table 2.

6. Conclusions

The flow of oxygen produced by ecosystems should be valued when its contributions to human wellbeing are observable, including: (1) for specific micro-scale areas (e.g., a forest or park) when extra high levels of atmospheric oxygen provides additional benefits to local human health and additional attraction to tourists; (2) when micro-scale oxygen production in water (e.g., a pond or aquafarm) avoids potential loss of aquatic products; and (3) when macro-scale oxygen production in marine water maintains crucial ecological and socioeconomic outcomes (e.g., fishery resources). However, whether macro-scale oxygen production in the atmosphere should be valued needs further research, because the short-term effects of declining global atmospheric oxygen need more evidence, regardless of being foreseeable in the long term.

Moreover, the value of oxygen production does not necessarily overlap, but can be aggregated, with carbon sequestration. However, to avoid double counting, the values of oxygen production and carbon sequestration should not be assessed based on the afforestation cost or duplicated in multiple ES categories (e.g., being added and counted in both climate and gas regulation). Depending on specific cases, potential techniques valuing oxygen production may include the revealed and stated willingness to pay for additional health benefits of breathing extra high levels of atmospheric oxygen, the market price of industrial oxygen, the travel cost to natural ‘oxygen bars’, the avoided cost of losing aquatic products and resources, and the replacement cost of using artificial techniques to produce oxygen in the atmosphere and water.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

Altieri, AH, Diaz, R 2019, ‘Dead zones: oxygen depletion in coastal ecosystems’, in: World Seas: An environmental Evaluation, Elsevier, pp. 453-473.

Altieri, A.H., Gedan, K.B., 2015. Climate change and dead zones. Global Change Biol. 21 (4), 1395–1406.

Altieri, A.H., Harrison, S.B., Seemann, J., Collin, R., Diaz, R.J., Knowlton, N., 2017. Tropical dead zones and mass mortalities on coral reefs. Proc. Natl. Acad. Sci. 114 (14), 3660–3665. https://doi.org/10.1073/pnas.1621517114.

Arowolo, A.O., Deng, X., Olatunji, O.A., Obayelu, A.E., 2018. Assessing changes in the value of ecosystem services in response to land-use/land-cover dynamics in Nigeria. Sci. Total Environ. 636, 597–609. https://doi.org/10.1016/j.scitotenv.2018.04.277.

Belcher, C., McElwain, J., 2008. Limits for combustion in low O2 redefine paleoatmospheric predictions for the Mesozoic. Science 321 (5893), 1197–1200. https://doi.org/10.1126/science.1160978.

Bowers, B., Flory, R., Ametepe, J., Staley, L., Patrick, A., Carrington, H., 2018. Controlled trial evaluation of exposure duration to negative air ions for the treatment of seasonal affective disorder. Psychiatry Res. 259, 7–14. https://doi.org/10.1016/j.psychres.2017.08.040.

Breitburg, D., Levin, L.A., Oschlies, A., Grégoire, M., Chavez, F.P., Conley, D.J., Garçon, V., Gilbert, D., Gutiérrez, D., Isensee, K., 2018, ‘Declining oxygen in the global ocean and coastal waters’, Science, 359(6371), p. eaam7240. doi:10.1126/science.aam7240.

Cai, S., Zhang, X., Cao, Y., Zhang, Z., Wang, W., 2020. Values of the Farmland Ecosystem Services of Qingdao City, China, and their Changes. J. Resour. Ecol. 11 (5), 443–453. https://doi.org/10.5814/j.issn.1674-764x.2020.05.002.

CBD, 2020a, Global Biodiversity Outlook 5, Secretariat of the Convention on Biological Diversity, Montreal, Canada.

CBD, 2020b, United Nations Decade on Biodiversity: Ecosystem services, <https://www.cbd.int/undb/media/factsheets/undb-factsheet-ecoserv-en.pdf>.

Chen, H., 2020. Complementing conventional environmental impact assessments of tourism with ecosystem service valuation: A case study of the Wulingyuan Scenic Area, China. Ecosyst. Serv. 43, 101100 https://doi.org/10.1016/j.ecoser.2020.101100.

Chen, H., 2021. The ecosystem service value of maintaining and expanding terrestrial protected areas in China. Sci. Total Environ. 781, 146768 https://doi.org/10.1016/j.scitotenv.2021.146768.

Chen, H., Costanza, R., Kubiszewski, I., 2022. Land use trade-offs in China’s protected areas from the perspective of accounting values of ecosystem services. J. Environ. Manage. 315, 115178 https://doi.org/10.1016/j.jenvman.2022.115178.

China National Environmental Management Standadisation Technical Commission 2020, Ecosystem assessment: Guideline for gross ecosystem product accounting, viewed 12 January 2022, <https://www.cnis.ac.cn/ynbm/zhfy/bzyjzq/gbyjzq/202010/t20201012_50375.html>.

Cole, D.B., Ozaki, K., Reinhard, C.T., 2022, ‘Atmospheric oxygen abundance, marine nutrient availability, and organic carbon fluxes to the seafloor’, Global Biogeochemical Cycles, 36(1), p. e2021GB007052. doi:10.1029/2021GB007052.

Costanza, R., d’Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O’neill, R.V., Paruelo, J., Raskin, R.G., 1997. The value of the world’s ecosystem services and natural capital. Nature 387, 253–260. https://doi.org/10.1038/387253a0.

Costanza, R., de Groot, R., Sutton, P., Van der Ploeg, S., Anderson, S.J., Kubiszewski, I., Farber, S., Turner, R.K., 2014. Changes in the global value of ecosystem services. Global Environ. Change 26, 152–158. https://doi.org/10.1016/j.gloenvcha.2014.04.002.

Costanza, R., de Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S., Grasso, M., 2017. Twenty years of ecosystem services: how far have we come and how far do we still need to go? Ecosyst. Serv. 28, 1–16. https://doi.org/10.1016/j.ecoser.2017.09.008.

de Groot, R., Brander, L., Van Der Ploeg, S., Costanza, R., Bernard, F., Braat, L., Christie, M., Crossman, N., Ghermandi, A., Hein, L., Hussain, S., Kumar, P., McVittie, A., Portela, R., Rodriguez, L.C., Ten Brink, P., Van Beukering, P., 2012. Global estimates of the value of ecosystems and their services in monetary units. Ecosyst. Serv. 1, 50–61. https://doi.org/10.1016/j.ecoser.2012.07.005.

de Groot, R.S., Wilson, M.A., Boumans, R.M., 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecol. Econ. 41 (3), 393–408. https://doi.org/10.1016/S0921-8009(02)00089-7.

Diaz, R.J., Rosenberg, R., 2008. Spreading dead zones and consequences for marine ecosystems. Science 321 (5891), 926–929. https://doi.org/10.1126/science.1156401.

FAO 2022, *Ecosystem Services & Biodiversity*, Food and Agriculture Organization of the United Nations, viewed 12 April 2022, <https://www.fao.org/ecosystem-services-biodiversity/background/regulating-services/en/>.

Fu, B.-J., Su, C.-H., Wei, Y.-P., Willett, I.R., Lü, Y.-H., Liu, G.-H., 2011. Double counting in ecosystem services valuation: causes and countermeasures. Ecol. Res. 26 (1), 1–14. https://doi.org/10.1007/s11284-010-0766-3.

Hein, L., Van Koppen, K., De Groot, R.S., Van Ierland, E.C., 2006. Spatial scales, stakeholders and the valuation of ecosystem services. Ecol. Econ. 57 (2), 209–228. https://doi.org/10.1016/j.ecolecon.2005.04.005.

Huang, J., Huang, J., Liu, X., Li, C., Ding, L., Yu, H., 2018. The global oxygen budget and its future projection. Sci. Bull. 63 (18), 1180–1186. https://doi.org/10.1016/j.scib.2018.07.023.

IPBES 2019a, Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services Secretariat, Bonn, Germany.

IPBES 2019b, Status and trends – drivers of change’, in ES Brondizio, J Settele, S Díaz & HT Ngo (eds), *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*, Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services Secretariat, Bonn, Germany.

Jiang, S.Y., Ma, A., Ramachandran, S., 2018. Negative air ions and their effects on human health and air quality improvement. Int. J. Mol. Sci. 19 (10), 2966. https://doi.org/10.3390/ijms19102966.

Jiang, H., Wu, W., Wang, J., Yang, W., Gao, Y., Duan, Y., Ma, G., Wu, C., Shao, J., 2021. Mapping global value of terrestrial ecosystem services by countries. Ecosyst. Serv. 52, 101361 https://doi.org/10.1016/j.ecoser.2021.101361.

Kasting, J.F., 2013. What caused the rise of atmospheric O2? Chem. Geol. 362, 13–25. https://doi.org/10.1016/j.chemgeo.2013.05.039.

Krause, A.J., Mills, B.J., Zhang, S., Planavsky, N.J., Lenton, T.M., Poulton, S.W., 2018. Stepwise oxygenation of the Paleozoic atmosphere. Nat. Commun. 9 (1), 1–10. https://doi.org/10.1038/s41467-018-06383-y.

Kubiszewski, I., Costanza, R., Dorji, L., Thoennes, P., Kuenga, T., 2013. An initial estimate of the value of ecosystem services in Bhutan. Ecosyst. Serv. 3, e11–e21. https://doi.org/10.1016/j.ecoser.2012.11.004.

Kubiszewski, I., Costanza, R., Anderson, S., Sutton, P., 2017. The future value of ecosystem services: Global scenarios and national implications. Ecosyst. Serv. 26, 289–301.

Lenton, T.M., Dahl, T.W., Daines, S.J., Mills, B.J., Ozaki, K., Saltzman, M.R., Porada, P., 2016. Earliest land plants created modern levels of atmospheric oxygen. Proc. Natl. Acad. Sci. 113 (35), 9704–9709. https://doi.org/10.1073/pnas.1604787113.

Li, T., Gao, X., 2016. Ecosystem services valuation of lakeside wetland park beside Chaohu Lake in China. Water 8 (7), 301. https://doi.org/10.3390/w8070301.

Li, J., Huang, P., 2018. An empirical study on the integration of rural tourism and meteorological from the perspective of global tourism. paper presented to 2018 3rd International Conference on Education, E-learning and Management Technology.

Liu, X., Huang, J., Huang, J., Li, C., Ding, L., Meng, W., 2020. Estimation of gridded atmospheric oxygen consumption from 1975 to 2018. J. Meteorolog. Res. 34 (3), 646–658. https://doi.org/10.1007/s13351-020-9133-7.

Lyons, T.W., Reinhard, C.T., Planavsky, N.J., 2014. The rise of oxygen in Earth's early ocean and atmosphere. Nature 506 (7488), 307–315. https://doi.org/10.1038/nature13068.

Maikhuri, R.K., Rao, K.S., 2012. Soil quality and soil health: A review. Int. J. Ecol. Environ. Sci. 38 (1), 19–37.

Mao, G.X., Lan, X.G., Cao, Y.B., Chen, Z.M., He, Z.H., Lv, Y.D., Wang, Y.Z., Hu, X.L., Wang, G.F., Jing, Y., 2012. Effects of short-term forest bathing on human health in a broad-leaved evergreen forest in Zhejiang Province, China. Biomedical Environ. Sci. 25 (3), 317–324. https://doi.org/10.3967/0895-3988.2012.03.010.

Millennium Ecosystem Assessment 2005, Ecosystems and human well-being: current state and trends, Washington, DC (USA) Island Press.

Müller, A., Sukhdev, P., Miller, D., Sharma, K., Hussain, S., 2015, Towards a Global Study on the Economics of Eco-Agri-Food Systems, The Economics of Ecosystems Biodiversity.

Newton, A., Brito, A.C., Icely, J.D., Derolez, V., Clara, I., Angus, S., Schernewski, G., Inácio, M., Lillebø, A.I., Sousa, A.I., 2018. Assessing, quantifying and valuing the ecosystem services of coastal lagoons. J. Nature Conserv. 44, 50–65. https://doi.org/10.1016/j.jnc.2018.02.009.

Ninan, K., Inoue, M., 2014. Valuing forest ecosystem services: What we know and what we don't. In: Forest, V., Ninan, K. (Eds.), Valuing Forest Ecosystem Services: Methodological Issues and Case Studies. Edward Elgar Publishing, pp. 189–226.

Ouyang, Z., Wang, X., Miao, H., 1999. A primary study on Chinese terrestrial ecosystem services and their ecological-economic values. Acta Ecol. Sin. 19 (5), 607–613. https://doi.org/10.1088/0256-307X/15/12/025.

Ozaki, K., Reinhard, C.T., 2021. The future lifespan of Earth's oxygenated atmosphere. Nat. Geosci. 14 (3), 138–142. https://doi.org/10.1038/s41561-021-00693-5.

Pino, O., La Ragione, F., 2013. There's something in the air: Empirical evidence for the effects of negative air ions (NAI) on psychophysiological state and performance. Res. Psychol. Behav. Sci. 1 (4), 48–53. https://doi.org/10.12691/rpbs-1-4-1.

Renforth, P., Henderson, G., 2017. Assessing ocean alkalinity for carbon sequestration. Rev. Geophys. 55 (3), 636–674. https://doi.org/10.1002/2016RG000533.

Sannigrahi, S., Chakraborti, S., Joshi, P.K., Keesstra, S., Sen, S., Paul, S.K., Kreuter, U., Sutton, P.C., Jha, S., Dang, K.B., 2019. Ecosystem service value assessment of a natural reserve region for strengthening protection and conservation. J. Environ. Manage. 244, 208–227. https://doi.org/10.1016/j.jenvman.2019.04.095.

Schmidtko, S., Stramma, L., Visbeck, M., 2017. Decline in global oceanic oxygen content during the past five decades. Nature 542 (7641), 335–339. https://doi.org/10.1038/nature21399.

Taye, F.A., Folkersen, M.V., Fleming, C.M., Buckwell, A., Mackey, B., Diwakar, K., Le, D., Hasan, S., Saint Ange, C., 2021. The economic values of global forest ecosystem services: A meta-analysis. Ecol. Econ. 189, 107145 https://doi.org/10.1016/j.ecolecon.2021.107145.

TEEB 2009, TEEB – The Economics of Ecosystems and Biodiversity for National and International Policy Makers, <http://www.teebweb.org/wp-content/uploads/Study%20and%20Reports/Reports/National%20and%20International%20Policy%20Making/TEEB%20for%20National%20Policy%20Makers%20report/TEEB%20for%20National.pdf>.

TEEB, 2019, Ecosystem Services, The Economics of Ecosystems & Biodiversity, Geneva, Switzerland, viewed 6 May 2019, <http://www.teebweb.org/resources/ecosystem-services/>.

UNEP 2014, Guidance Manual on Valuation and Accounting of Ecosystem Services for Small Island Developing States, United Nations Environment Programme, <https://www.cbd.int/financial/monterreytradetech/unep-valuation-sids.pdf>.

United Nations et al. 2021, *System of Environmental-Economic Accounting—Ecosystem Accounting (SEEA EA)*, White cover publication, <https://seea.un.org/ecosystem-accounting>.

Wallace, K., 2007. Classification of ecosystem services: problems and solutions. Biol. Conserv. 139 (3–4), 235–246. https://doi.org/10.1016/j.biocon.2007.07.015.

Wang, J., Yang, Y., Jiang, X., Xiao, Y., Deng, G., Qian, Y., Gu, X., 2022. Influence of meteorological conditions on the negative oxygen ion characteristics of well-known tourist resorts in China. Sci. Total Environ. 819, 152021 https://doi.org/10.1016/j.scitotenv.2021.152021.

Wei, Y., Wu, J., Huang, J., Liu, X., Han, D., An, L., Yu, H., Huang, J., 2021. Declining oxygen level as an emerging concern to global cities. Environ. Sci. Technol. 55 (12), 7808–7817.

World Resource Institute 2022, *Global Historical Emissions*, viewed 24 April 2022, <https://www.wri.org/insights/history-carbon-dioxide-emissions#:~:text=%20The%20History%20of%20Carbon%20Dioxide%20Emissions%20,the%20largest%20in%20the%20world.%20Interestingly%2C...%20More%20>.

Xue, D., Tisdell, C., 2001. Valuing ecological functions of biodiversity in Changbaishan Mountain Biosphere Reserve in northeast China. Biodivers. Conserv. 10 (3), 467–481. https://doi.org/10.1023/A:1016630825913.

Zhao, H., Li, W., Ma, A., He, Y., 2004. Valuation of barely agro-ecosystem services in Lhasa River valley region: A case study of Dazi County. J. Natural Resour. 19 (5), 632–636.

Zhu, S.-x., Hu, F.-f., He, S.-y., Qiu, Q., Su, Y., He, Q., Li, J.-y., 2021. Comprehensive evaluation of healthcare benefits of different forest types: A case study in Shimen National Forest Park, China. Forests 12 (2), 207. https://doi.org/10.3390/f12020207.