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SUPPLEMENTARY INFORMATION

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Planetary boundaries for a blue planet

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Supplementary Information for

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Supplementary Note 1: Glossary

Albedo: The proportion of solar radiation that is reflected from the earth's surface.

Control variable: Driver of the state of a system. Current value of the control variable can be estimated to track the state of system relative to a boundary value e.g. carbon dioxide emissions drive changes in global temperature.

Evapotranspiration: Transfer of moisture from the earth's surface and vegetation into the atmosphere.

Great Acceleration: describes accelerating changes in a wide range of socio-economic (e.g. human population and resource use) and earth system attributes (e.g. global temperatures and ocean acidification) since the mid-20th century.

Model ensembles: Combining and comparing outputs from two or more models to improve accuracy of predictions and better understand uncertainty around model results.

Regime shift: Change in the structure and function of an ecosystem, where distinct regimes are underpinned by different feedbacks and processes (e.g. shift from kelp forests to urchin barrens).

Response variable: Variable describing the state of a system e.g. global temperature.

Sea-floor integrity index: Defined by Rice *et al.* [1] as an index that incorporates indicators on "(i) type, abundance, biomass and areal extent of relevant biogenic substrate; (ii) extent of the seabed significantly affected by human activities for the different substrate types; (iii) presence of particularly sensitive and/or tolerant species; (iv) multi-metric indices assessing benthic community condition and functionality, such as species diversity and richness,

proportion of opportunistic to sensitive species; (v) proportion of biomass or number of individuals in the macrobenthos above some specified length/size; and (vi) parameters describing the characteristics (shape, slope and intercept) of the size spectrum of the benthic community."

Sub-boundary: Although nine biophysical processes were identified in the planetary boundaries framework, some of these boundaries have been split into two sub-boundaries that represent different but complementary components of the main boundary. For example, the biogeochemical flows boundary is represented by two sub-boundaries – nitrogen and phosphorous.

Threshold (Tipping point): Region of accelerating change in the relationship between response and control variables, in this context, between the condition of a system (e.g. algae or coral dominated) and a driver (e.g. herbivory).

Supplementary Note 2: Literature review of planetary boundaries research

A comprehensive search of the ISI Web of Science (WoS) and Scopus databases (2009–2016) was conducted using the phrase "planetary boundaries". We used both WoS and Scopus databases because they search an overlapping but slightly different range of journals, and we chose not to search Google Scholar because it provides less consistent search results than the other two databases [2]. Our search returned 208 papers, reports and book chapters that used this phrase in the title, abstract or keywords. We were unable to access 31 of these documents, primarily book chapters. From the remaining literature we selected only those documents referring to the Planetary Boundaries framework of [3]. One hundred and sixty-eight documents remained. We reviewed each document and classified it according to year of publication, discussion of specific ecosystems in relation to setting boundaries and governance (Supplementary Figure 1).

Supplementary Note 3: Estimation of global distribution of human appropriated primary production (HANPP)

Terrestrial estimates of HANPP represent the percentage of potential primary productivity that is utilized through land conversion and harvesting. Estimates represent a 5-year average value (1998 to 2002). Methods for estimating the percentage of net primary production appropriated by humans for terrestrial systems are detailed in [4] and data are available online at: https://www.uni-klu.ac.at/socec/inhalt/1191.htm.

Marine estimates of HANPP represent the percentage of available primary productivity that is harvested in global marine fisheries. Available primary production estimates were derived using the model described by [5], with a spatial resolution of 9km. This approach computes depth-integrated primary production from chlorophyll pigment concentration based on SeaWiFS satellite data and photo-synthetically active radiation as calculated in [6], and processed by the Inland and Marine Waters Unit (IMW), Institute for Environment and Sustainability, EU Joint Research Center (JRC), Ispra, Italy. Estimates represent a 5-year average value (1998 to 2002).

The harvested primary productivity was based on annual average global harvest estimates within 30-min spatial cells for this same time period [7]. Global harvest data are publicly available at http://dx.doi.org/10.4226/77/58293083b0515 [8]. Each type of harvested seafood was assigned an average adult trophic level [9]. The primary production required to support this harvest was described by [10] in the form:

$$PPR = \sum_{i=1}^{n} \frac{C_i}{CR} * \left(\frac{1}{TE}\right)^{(TL_i - 1)}$$

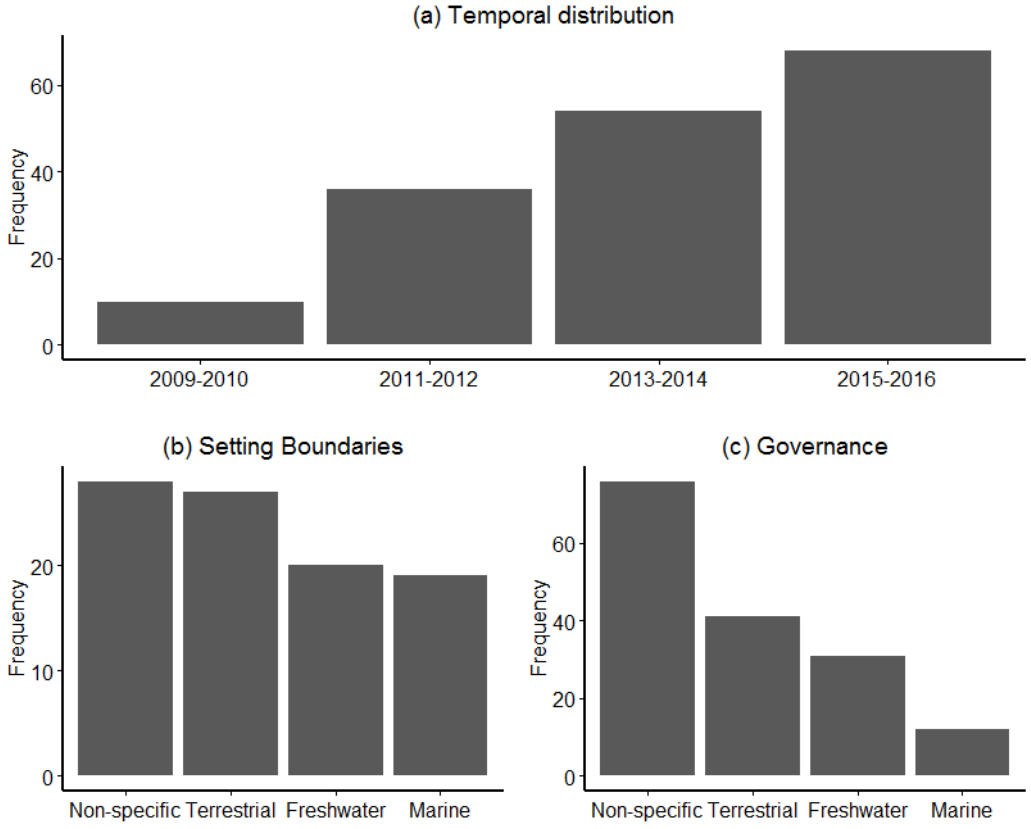
where C_i is the catch of species I, CR is the conversion rate of wet weight to carbon, TE is the transfer efficiency between trophic levels, TL_i is the trophic level of species i and n is the number of species caught in a given area. We applied a 9:1 ratio for CR [10]. Species-specific trophic levels, usually derived from diet composition data, were taken from FishBase (www.fishbase.org) for fishes and SeaLifeBase (www.sealifebase.org) for invertebrates. Unlike [10] and [9], which assumed a 10% transfer efficiency between all trophic levels, we used varying transfer efficiencies between trophic levels. We used the mean of the range of values extracted by [11] from global ecosystem models (Supplementary Table 1). These allow for greater and more realistic transfer efficiencies of carbon at lower trophic levels and therefore harvests do not require as much of available primary production as [9] and others have calculated.

Our estimate of HANPP in marine systems does not account for habitat conversion. Accounting for the effects of habitat conversion is an important next step in building understanding of spatial and temporal patterns in HANPP for marine systems.

Supplementary Table 1: Trophic efficiency schedule detailing percentage energy transfer among trophic levels. Mean values of percentage range were used to estimate transfer of energy. Ranges sourced from [11].

Trophic Level	Percentage transfer
TL0->TL1	15-45%
TL1->TL2	15-20
TL3->TL4	13-15
TL4->TL5	9-12
TL5->TL6	8-10
TL6->TL7	7-9
TL7->TL8	3-8

Supplementary Figure 1: Publications referencing 'planetary boundaries' (n=168). (A) Temporal distribution of publications; Publications (B) discussing the setting of boundaries using ecosystem specific information, and (C) governance of different systems. In (B) and (C) where a study discussed more than one system, all are reported**.**



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