

Supplementary material

A systematic review on trade-off analysis in agriculture

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1 Supplementary figures

In addition to those listed in the main manuscript, the following R packages were used for data handling and visualizations: readxl (Wickham and Bryan, 2019), scales (Wickham and Seidel, 2020), reshape2 (Wickham, 2007), maps (Becker et al., 2018), forcats (Wickham et al., 2021), and wordcloud (Fellows, 2018).

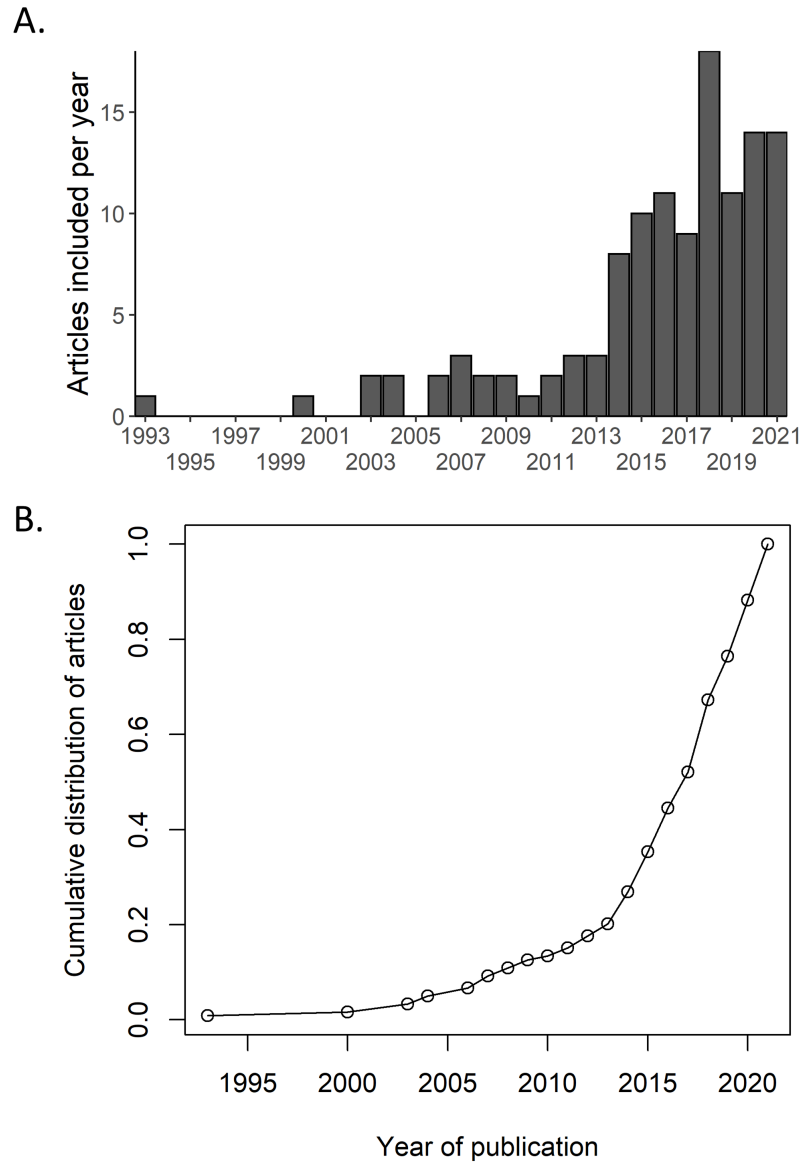
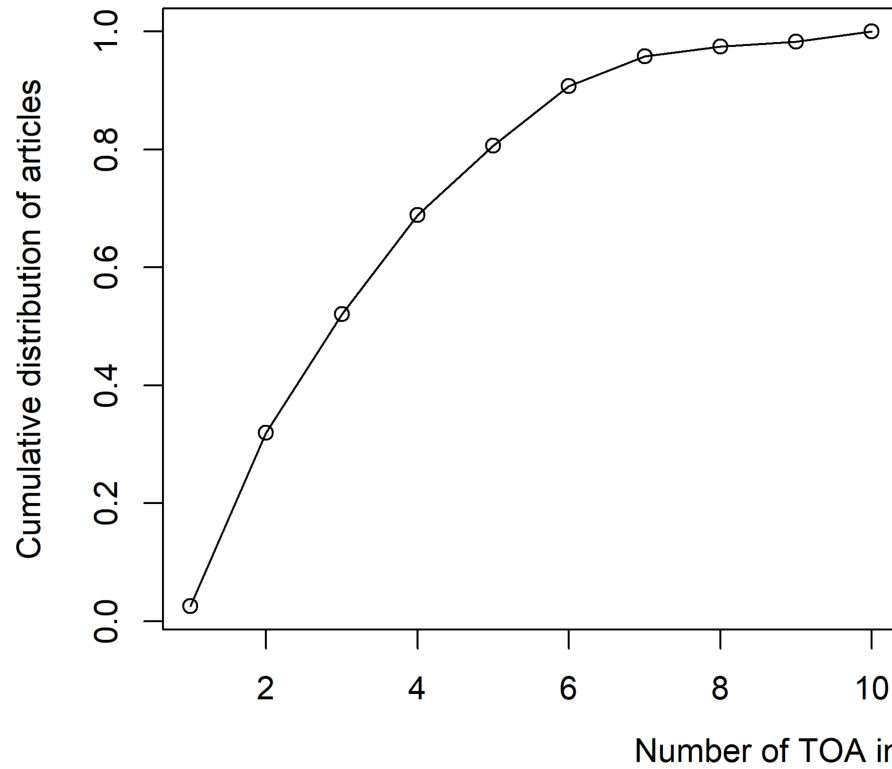


Figure 1: Articles per publication year (A.) and its cumulative distribution (B.)

A.



B.

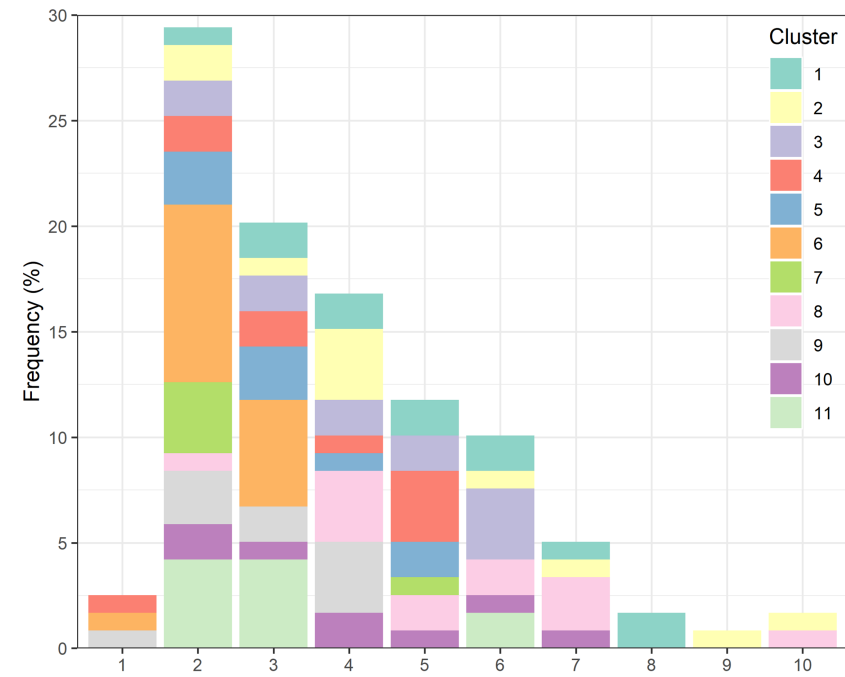


Figure 2: A.) Cumulative distribution of articles per number of TOA indicators included within an article; B.) frequency for the number of TOA indicators included in article, color-coded by the corresponding cluster as identified in Fig. 1 in the main manuscript

2 Supplementary tables

Table S1 – Definitions of the criteria logged during the systematic review and their associated levels

Criterion	Description	Levels
TOA method	Primary method(s) applied to generate values for the TOA indicators.	1=Simulation modelling (spatially explicit); 2=Simulation modelling (parsimonious); 3=Optimization methods; 4=Cost-benefit analysis/Economic surplus; 5=Econometrics; 6=Qualitative approaches; 7=Meta-analysis, systematic-review; 8=Spatial analysis, GIS, Remote sensing; 9=Other
TOA spatial scale	The spatial scale at which the trade-off indicators are evaluated	1= Field; 2=Farm; 3=Region; 4=National; 5=Multi-country; 6=Global; 7=Other
Discipline	At which spatial scale a discipline (Crop, Economic, Livestock, Environment, Fisheries, Forestry) is considered within the modelling/data collection/analysis.	1= Field; 2=Farm; 3=Region; 4=National; 5=Multi-country; 6=Global; 7=Other
<i>TOA indicators: Economic</i>		
Profitability	Indicator that quantifies the financial gain (e.g. net revenue)	0=No; 1=Yes

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Criterion	Description	Levels
Poverty	Indicator that quantifies the number of individuals below a set threshold at which they are not able to afford an adequate standard of living (e.g. number of farmers within the case-study domain that earn an income below a monetary threshold)	0=No; 1=Yes
Market supply demand	Indicator that quantifies the change in market supply/demand of a commodity	0=No; 1=Yes
Assets	Indicator that quantifies anything tangible/intangible that is owned/controlled by an individual/community to produce value and that is held to have positive economic value (e.g. cattle herd density within a farm)	0=No; 1=Yes
Labor productivity	Indicator that quantifies the production of a desired output as a function of the amount of labor (e.g. share of farmland to produce a specified number of calories within a region)	0=No; 1=Yes
<i>TOA indicators: Sustainable resource management</i>		
Biodiversity	Indicator that quantifies the variability among living organisms from all sources and the ecological complexes of which they are part (e.g. richness/evenness indices)	0=No; 1=Yes
Soil organic carbon	Indicator that quantifies the soil organic carbon stock within a given model domain	0=No; 1=Yes
Soil nutrients	Indicator that quantifies the stock of soil nutrients within a given model domain	0=No; 1=Yes
Soil erosion	Indicator that quantifies the removal/retention of soil surface material within a given model domain	0=No; 1=Yes
Water quality	Indicator that quantifies physical, chemical and biological characteristics of water	0=No; 1=Yes

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Criterion	Description	Levels
Water quantity	Indicator that quantifies the volume of water within a given model domain (e.g. share of hydrological flow contributed to agriculture)	0=No; 1=Yes
Energy	Indicator that quantifies a variable relevant to energy within the model domain (e.g. usage/availability)	0=No; 1=Yes
GHG	Indicator that quantifies the discharge of greenhouse gases, such as carbon dioxide, methane, nitrous oxide and various halogenated hydrocarbons, into the atmosphere	0=No; 1=Yes
Land use	Indicator that quantifies arrangements, activities and inputs people undertake in a certain land cover type to maintain it or produce change	0=No; 1=Yes

TOA indicators: Human well-being

Gender equity	Indicator that quantifies the fairness of treatment for women and men according to their respective needs	0=No; 1=Yes
Empowerment	Indicator that quantifies the enhancement of the assets and capabilities of diverse individuals and groups to function, engage, influence, and/or hold accountable the institutions that affect them.	0=No; 1=Yes
Food security	Indicator that assesses the reliable physical and economic access to nutritious and sufficient food	0=No; 1=Yes
Health	Indicator that quantifies the state of functioning optimally without evidence of disease	0=No; 1=Yes
Nutrition	Indicator that quantifies a (set of) variable(s) relevant to the food intake required for health and growth (e.g. calories to proteins ratio produced at a farm)	0=No; 1=Yes

TOA indicators: Agronomic

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Criterion	Description	Levels
Yield	Indicator that quantifies the total harvest/production from a farm	0=No; 1=Yes
Yield stability	Indicator that quantifies the change in agricultural yield given a constraint or scenario	0=No; 1=Yes
Input efficiency	Indicator that quantifies the input/output ratio of variables relevant to production	0=No; 1=Yes
Land use efficiency	Indicator that quantifies the input/output ratio of a (set of) variable(s) relevant to arrangements, activities and inputs people undertake in a certain land cover type to maintain it or produce change for a spatial unit	0=No; 1=Yes
Self sufficiency	Indicator that quantifies the extent to which the given model domain unit (e.g. farm, region) can supply in its dietary/nutritional needs	0=No; 1=Yes
<i>Stakeholders</i>		
Stakeholder	Whether individuals, groups, organizations or sectors in society that have a clearly identifiable interest within the TOA context have been reported to be included within the case-study	0=No; 1=Yes
Experts	–	0=No; 1=Yes
Governments	–	0=No; 1=Yes
Farmers	–	0=No; 1=Yes
Academia	–	0=No; 1=Yes
Private sector	–	0=No; 1=Yes
Environmental organizations	–	0=No; 1=Yes

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Criterion	Description	Levels
Local beneficiaries	Persons within TOA case-study area that do not fall under other categories (e.g. civil society stakeholders)	0=No; 1=Yes
Distant beneficiaries	Persons outside TOA case-study area (but are affected by TOA) that do not fall under other categories	0=No; 1=Yes
Stakeholder involvement	Which type of stakeholder engagement has been employed within the TOA	1=Consultation; 2=Co-development; 3=Valuation; 4=Validation
<i>Other</i>		
Scenario	Whether a postulated sequence of events is used within the analysis and if so, which type of events are included	1=Climate; 2=Policy; 3=Behavioral; 4=Demography; 5=Economic; 6=Resource usage; 7=Other; 8=None
System border	Whether the TOA case-study area has been defined based on biophysical or administrative boundaries	1=Biophysical; 2=Administrative; 3=Both; 4=Other
Off-site	Whether off-site effects (those occurring outside the case-study area) have been considered within the TOA. E.g. environmental processes at larger scales/trade-mediated effects.	0=No; 1=Yes
Uncertainty	Whether a state of incomplete knowledge has been recognized, either due to a lack of information or a disagreement about what is known/knowable	0=No; 1=Yes
Validation	Whether the case-study performs a validation of results obtained by data collection, the modelling procedure or the outcomes and recommendations from the TOA	0=No; 1=Yes

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Criterion	Description	Levels
Risk analysis	Whether the inference from the TOA and any subsequent recommendations account for associated risks	0=No; 1=Yes
Cross-scale analysis	Whether models that inform the TOA have been integrated across scales; Aggregative=Model frameworks that aggregate model outputs at lower scales to use as inputs at higher scales; Interactive=Model frameworks that have sub-models operating at different spatial and temporal resolutions	1=Aggregative; 2=Interactive; 3=None
Data visualization	Visualization method applied to compare across TOA indicators	1=Tabular matrix; 2=Bar charts; 3=Scatterplots/Pareto-frontier; 4=Spider/radial/petal/polar diagrams; 5=Maps; 6=Line graph; 7=Other
Data type informing indicators	The type of data that has been used to inform the TOA analysis and therefore modelling of the relative changes of indicators	1=Primary; 2=Secondary; 3=Elicitation; 4=Proxy; 5=Models
ESS	Whether the study considers the TOA indicators within an ecosystem services methodological framework	0=No; 1=Yes
Farming system	Descriptive information on farming system	Aposteriori classification
Farm management	Descriptive information on management on farms considered within the TOA	Aposteriori classification
Knowledge gap	Descriptive information on remaining knowledge gaps based on TOA	Aposteriori classification
Synergy	Whether synergies are also identified within the TOA	0=No; 1=Yes

3 Additional figures not referenced within manuscript

3.1 Articles by human development index

With regards to the logging of criteria relevant to countries: Some corresponding authors listed affiliated institutes within multiple countries. In that case, the institute listed as first affiliation and its respective location was registered. Furthermore, some articles considered a case-study that spanned multiple countries. In that case, all countries have been included. Global studies (n=1) have been excluded from all maps.

“The human development index (HDI) is composite index measuring average achievement in three basic dimensions of human development—a long and healthy life, knowledge and a decent standard of living” (UNDP, 2020). The HDI values for the year 2019 have been used, the classifications (low, medium, high, very high) are provided by the UNDP for each year.

Figure 3 shows that based on the countries that occur with a frequency > 1 , the lead author’s affiliation does not include countries in the lower two categories of the human development index (HDI) except for Kenya, Pakistan and Ethiopia (left-panel). However, countries where the case-study areas are located show a much larger share of countries in the lower two categories of the HDI (right-panel) as it also includes Zimbabwe, Senegal, Mali, Zambia, Tanzania, Ghana, Uganda, Rwanda, Mauritania, Guinea, Cameroon, Benin and Angola.

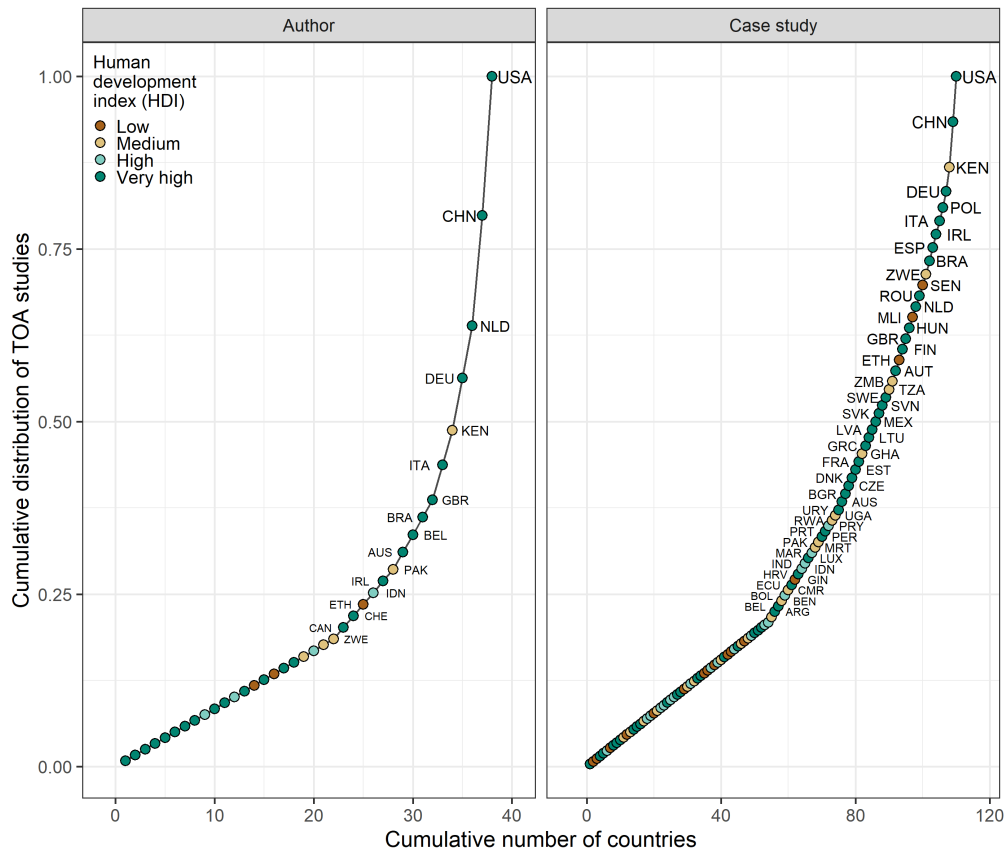


Figure 3: Cumulative distribution of TOA articles versus cumulative number of countries, both in terms of the corresponding author's affiliation and case-study area. Colors indicate the four classifications of the human development index (HDI) as provided by the UNDP for 2019.

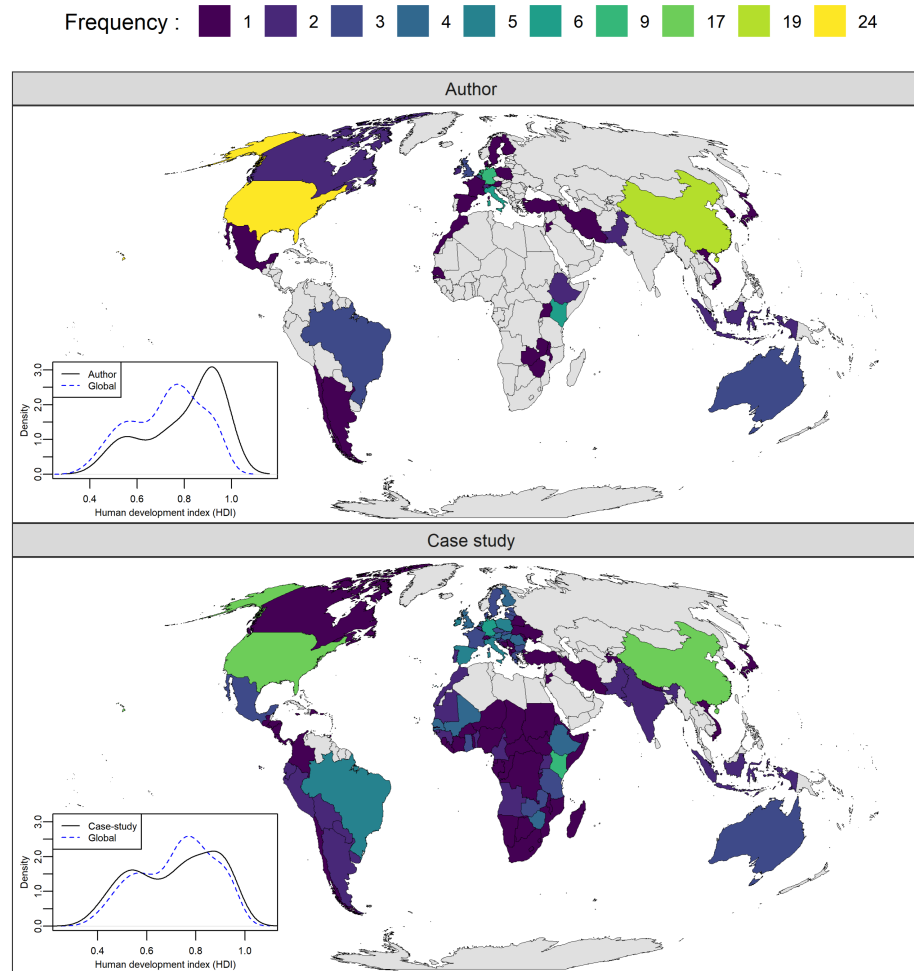


Figure 4: The frequency of a country as the location for the corresponding author's affiliation or the case-study area. Inset shows the density distributions of the human development index (HDI) for the author's affiliation and case-study area together with the density curves for all countries included in the HDI (Global).

3.2 Geographical trends of articles on TOA in agriculture

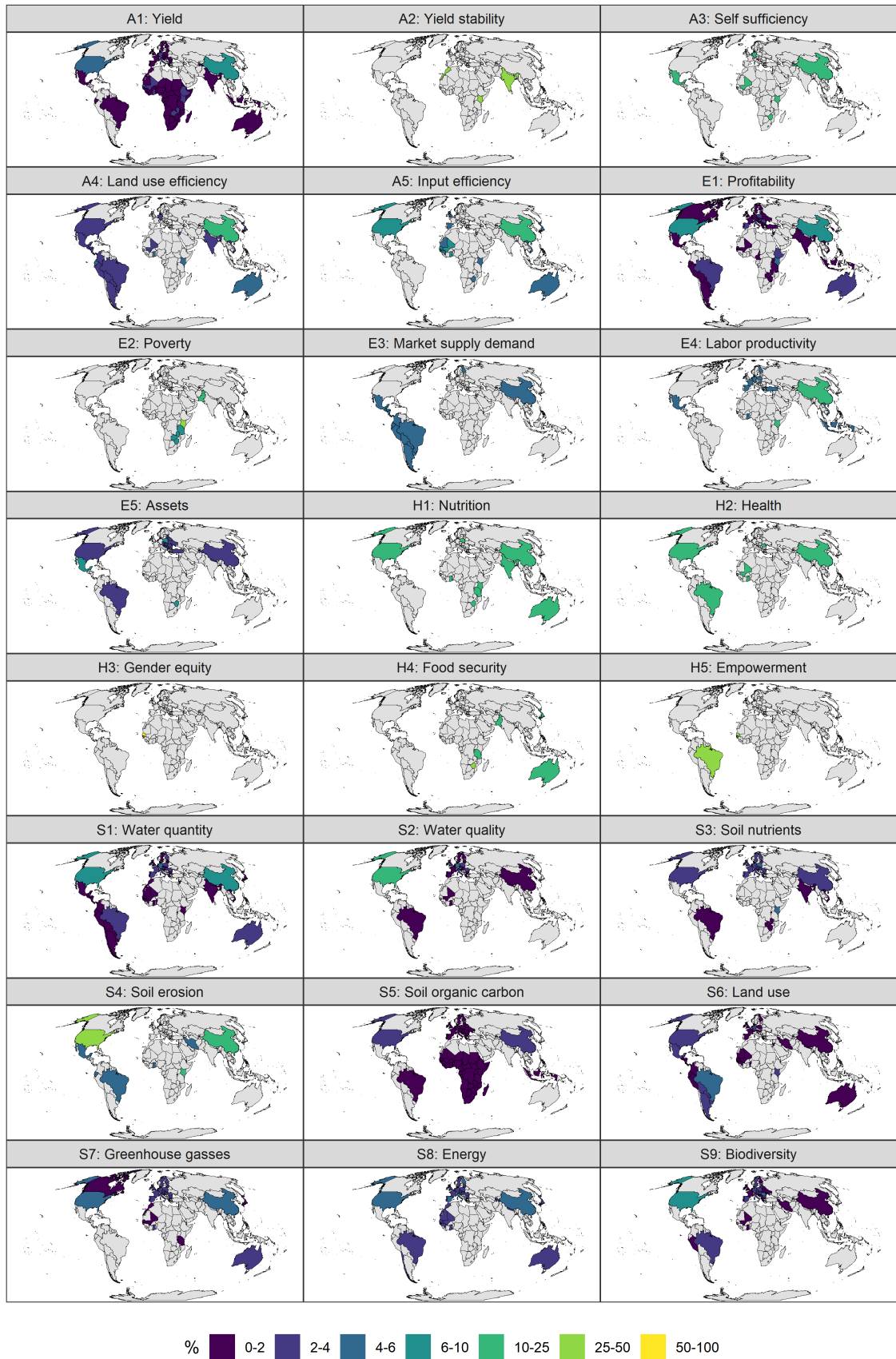


Figure 5: The relative frequency of a country in which the case-study area was located for each TOA indicator included within the article. The frequency of countries sums to 100% for each indicator panel.

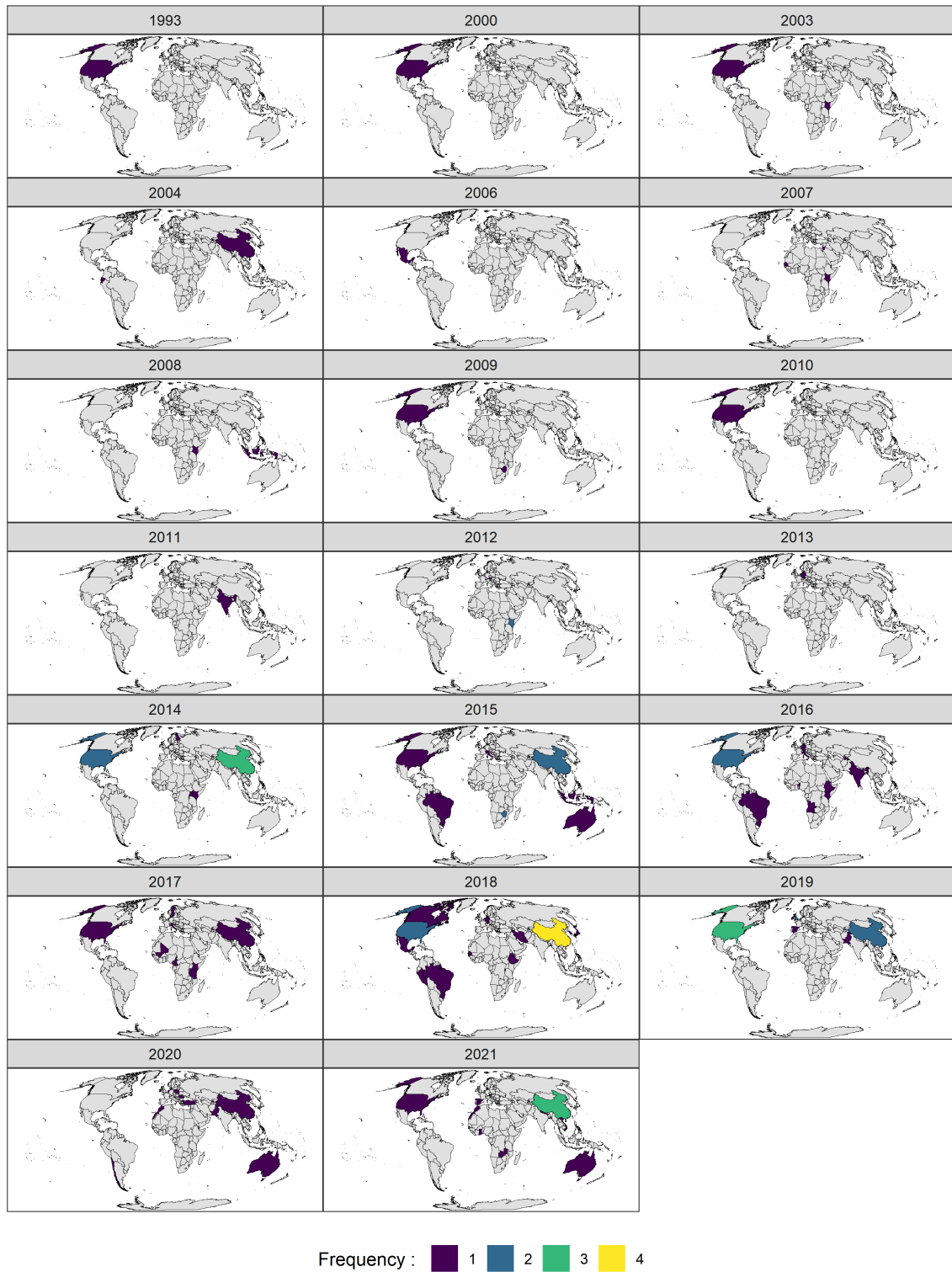


Figure 6: The frequency of a country in which the case-study area was located, plotted as a time series of publication date.

3.3 Cluster analysis

The cluster analysis (Fig. 1 in main manuscript) showed a clear distinction between articles that considered the TOA within an ecosystem services methodological framework (ESS). Results for this criterion were not reported in the main manuscript (see also the supplementary material included with the manuscript that contains the raw data).

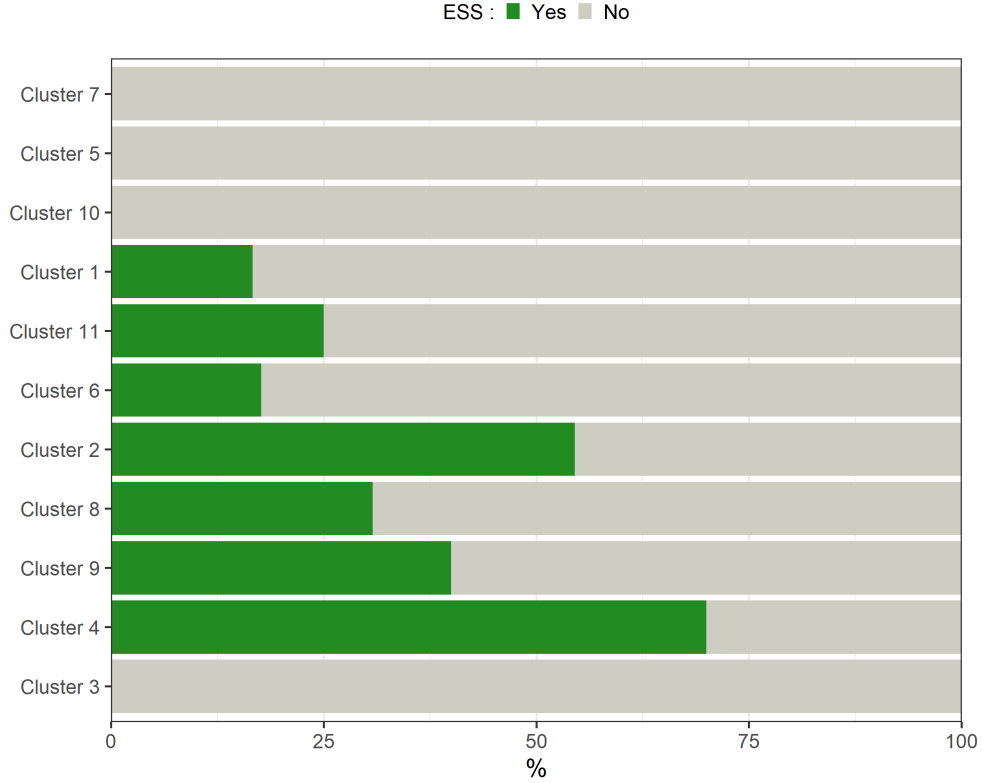


Figure 7: The frequency of whether an ecosystem services (ESS) methodological framework has been applied within an article, binned by each cluster

Fig. 8 shows the frequency of which system border was used to delineate the case-study area, binned by each cluster. Clusters that delineated the case-study area by administrative boundaries only (clusters 5 and 8) were characterized by economic, human health and agronomic indicators. Cluster 2 showed the highest share of biophysical delineation and was concerned with water quantity/quality, reflecting the use of watershed boundaries. Furthermore, 54 articles (43%) assessed biophysical indicators within their TOA but the case-study area was delineated by administrative boundaries only (not shown in graph).

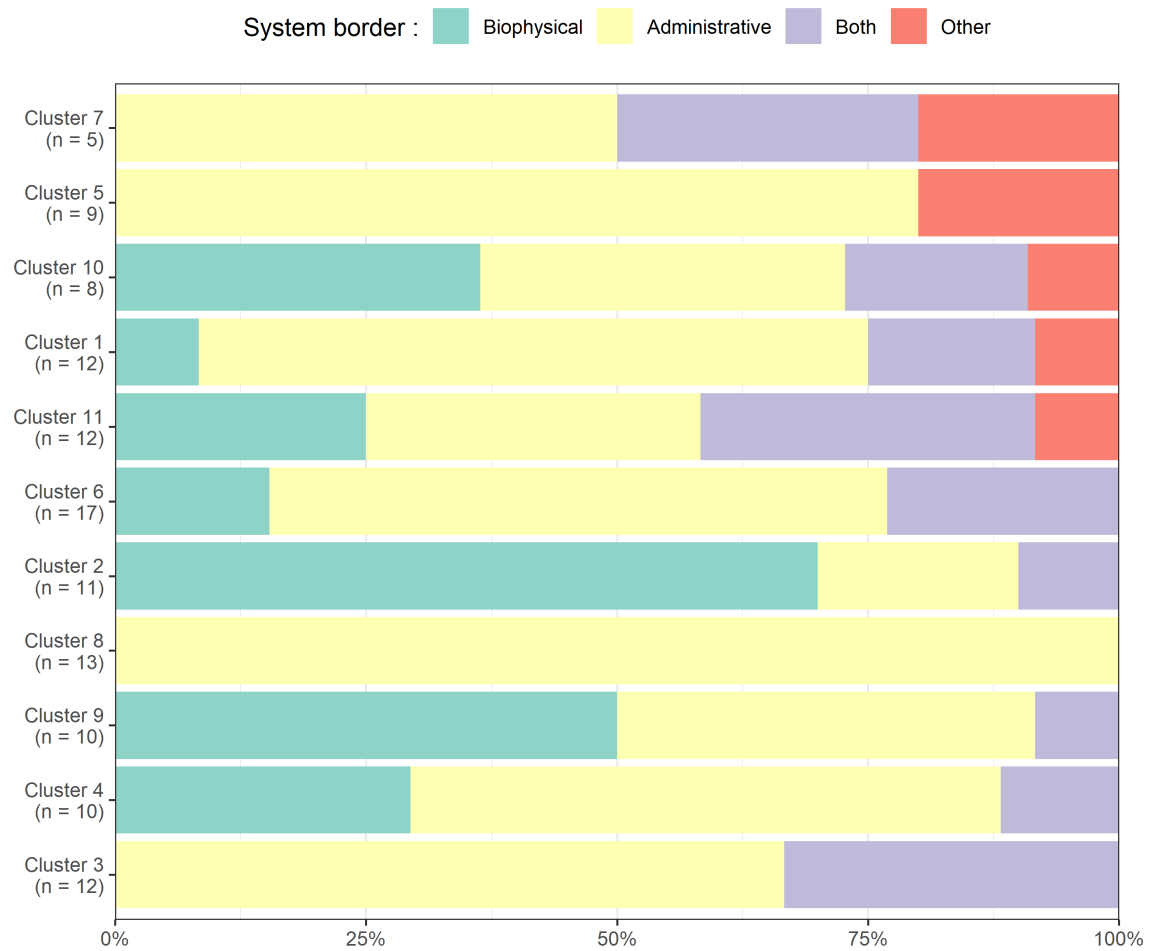


Figure 8: The frequency in which the TOA case-study area defined by administrative or biophysical borders for each cluster

3.4 Wordclouds

This section reports on wordclouds based on three qualitative criteria: farming system, farm management and reported knowledge gaps in the article’s discussion section (see methodology main manuscript). Wordclouds have been generated by plotting words with a minimum frequency of three and a maximum of 100 words. Redundant words have been removed based on visual inspection.

One can infer from the wordcloud that ‘small-holder’ farms are the most prominent farming system studied, followed by ‘livestock’ and ‘crop-livestock’ production systems. This is not reflected within Fig. 3E in the main manuscript, where livestock took up a low share. This might show that the livestock component of the agricultural system under study is often disregarded or only accounted for implicitly. However, this wordlcoud is based on a smaller sample ($n = 81$) as not all articles explicitly listed the farming system under study. These words are followed by ‘silviculture’, ‘semi-subsistence’ and ‘small-scale’, mixed agriculture.



Figure 9: Word cloud for the “farming system” criterium (n=71)

A total of 99 articles from the sample reported knowledge gaps which have been visualized by a word cloud. The most prominent words are ‘water’ (26%) and ‘ecosystem services’ (24%). The latter indicates the frequency in which a need to include other ecosystem services is expressed in articles that adopt an ESS framework (24% of articles adopted an ESS framework).

The next two categories indicate the frequent mention that TOA should be performed for different crops (17—18%) (yellow category) and the words ‘climate’, ‘economic’ and ‘management’ (15—16% occurrence, in green). Words such as ‘land use change’, ‘policy’ and ‘data’ indicate that these factors need ‘additional’ study or be accounted for (‘account’) (10—13% occurrence).

The fourth category (purple) lists words relative to how the TOA framework is defined (‘scale’ (9%) and ‘levels’, ‘multiple’, ‘objectives’, ‘inclusion’ and ‘stakeholders’ occurring in 7% of the articles) as well as the study’s robustness: ‘uncertainty’, ‘constraints’, ‘required’ (7—8%). With additional mention of TOA indicators (‘GHG’ (9%) and ‘biodiversity’, ‘soil carbon’, ‘land use’, ‘yield’ and ‘market’ occurring in 7% of the articles). It also lists ‘impacts’ (9%), ‘decision-making’ and ‘performance’ (7%), illustrating the need to use TOA results within an applied policy- and decision-making context.

Lastly, some words in orange include TOA indicators which showed a low frequency in Fig. 2A in the main manuscript: ‘human’ (6%) and ‘labor’, ‘supply’, ‘nutrient’ (4—5%) as well as two TOA indicators that showed a medium frequency in Fig. 2A in the main manuscript: ‘species’ (biodiversity) and ‘energy’ (4%).

3.5 Time series figures

This section reports time series plots of different criteria.

3.5.1 Multi-level criteria

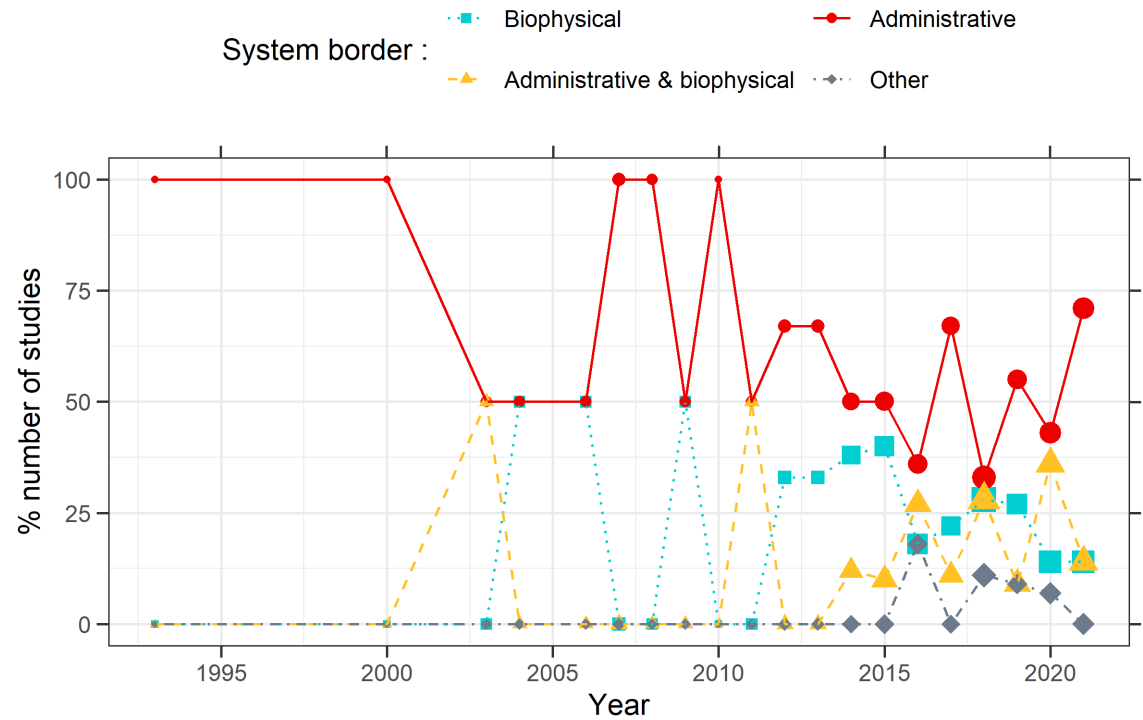


Figure 12: System border that is applied to define the TOA domain as a function of publication date. Point size indicates the number of articles per year in the sample.

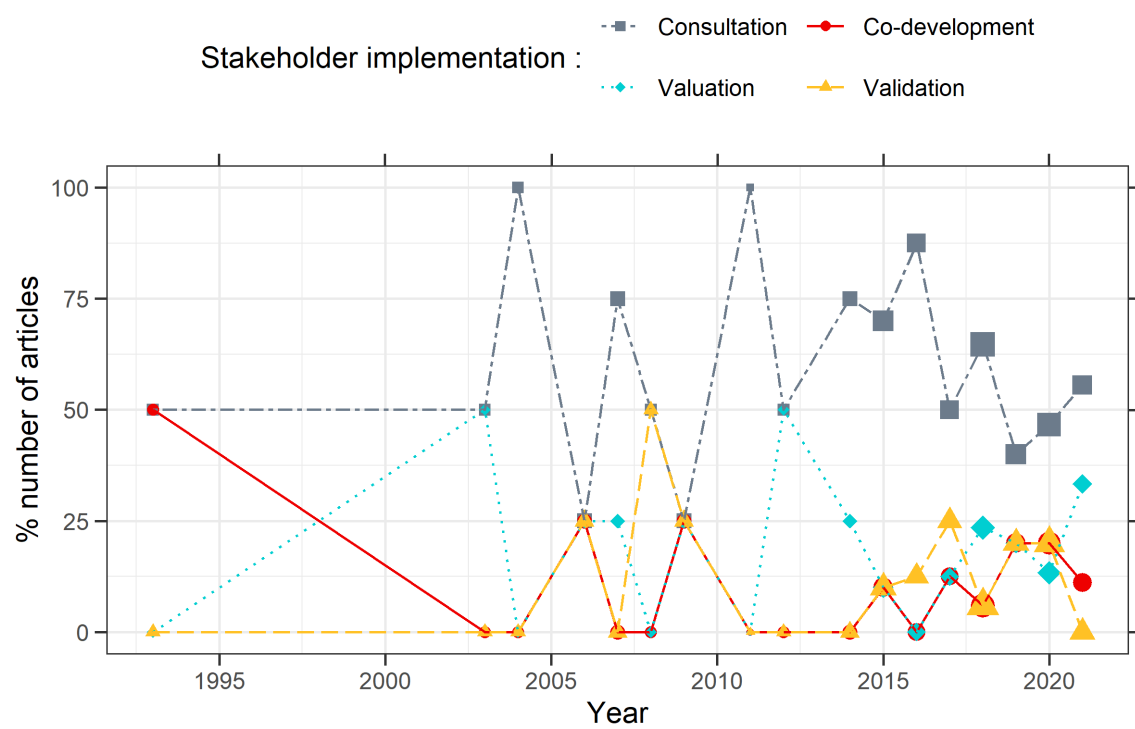


Figure 13: Stakeholder implementation considered as a function of publication date. Point size indicates the number of articles per year in the sample.

3.5.2 Binary criteria

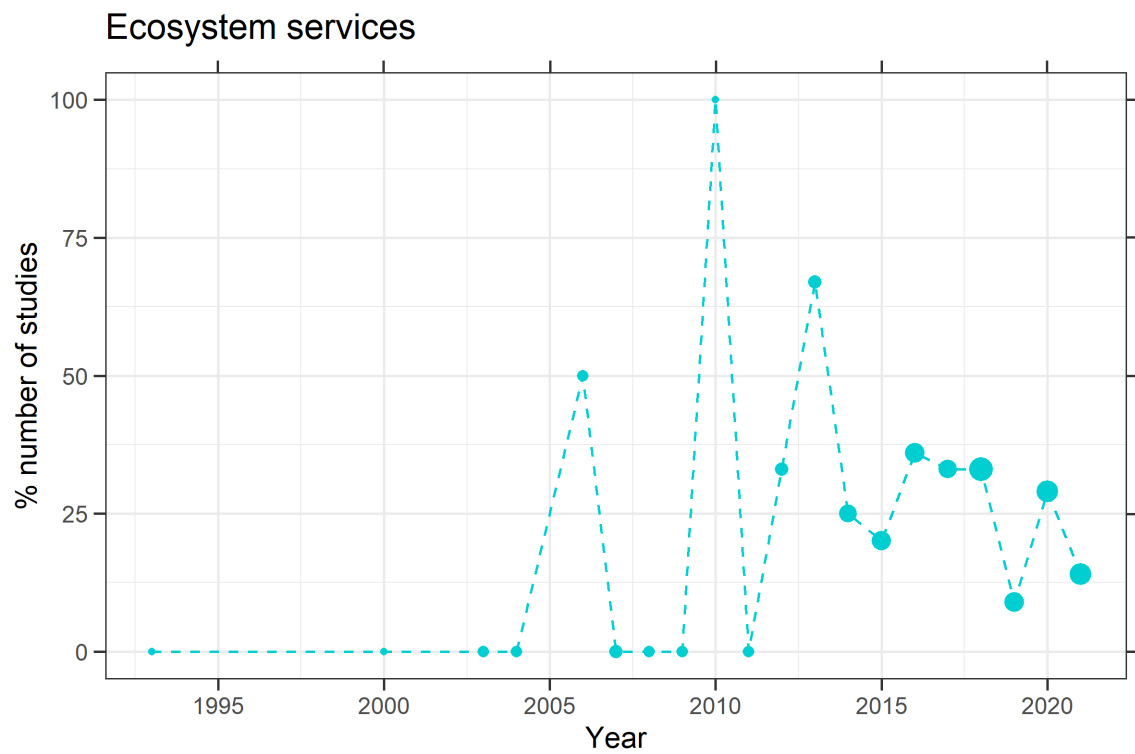


Figure 14: Whether the article adopted an ecosystem services methodological framework as a function of publication date. Point size indicates the number of articles per year in the sample.

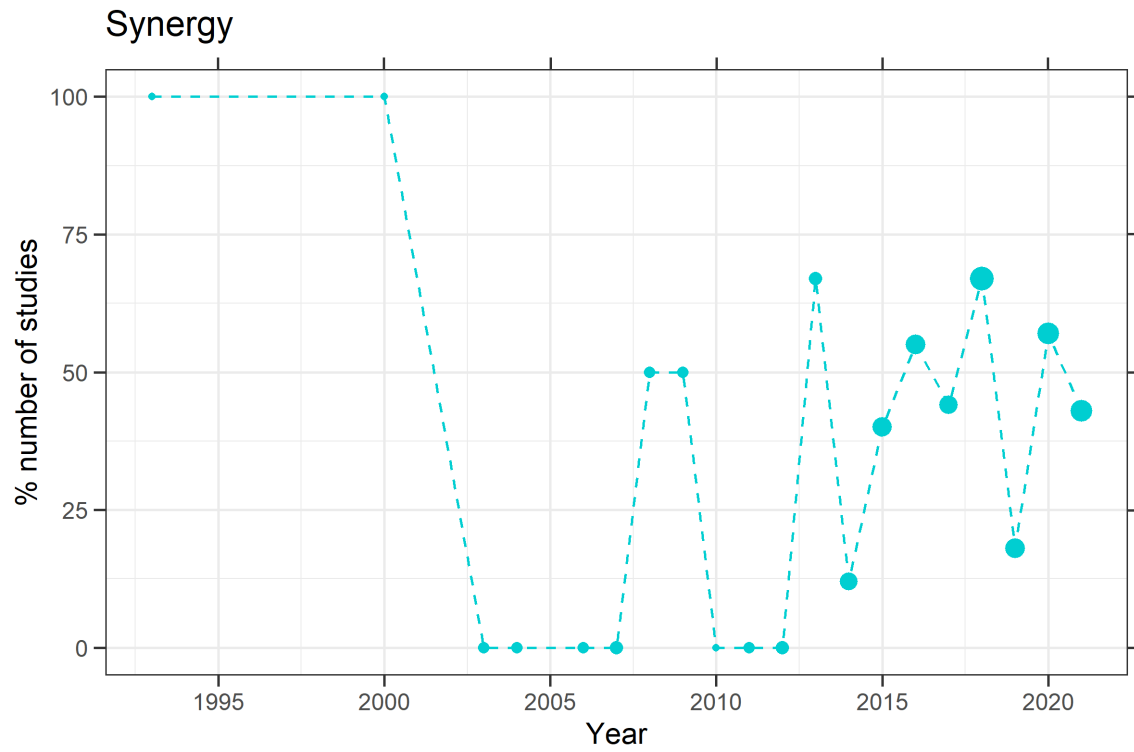


Figure 15: Whether the article considered synergies as well as trade-offs as a function of publication date. Point size indicates the number of articles per year in the sample.

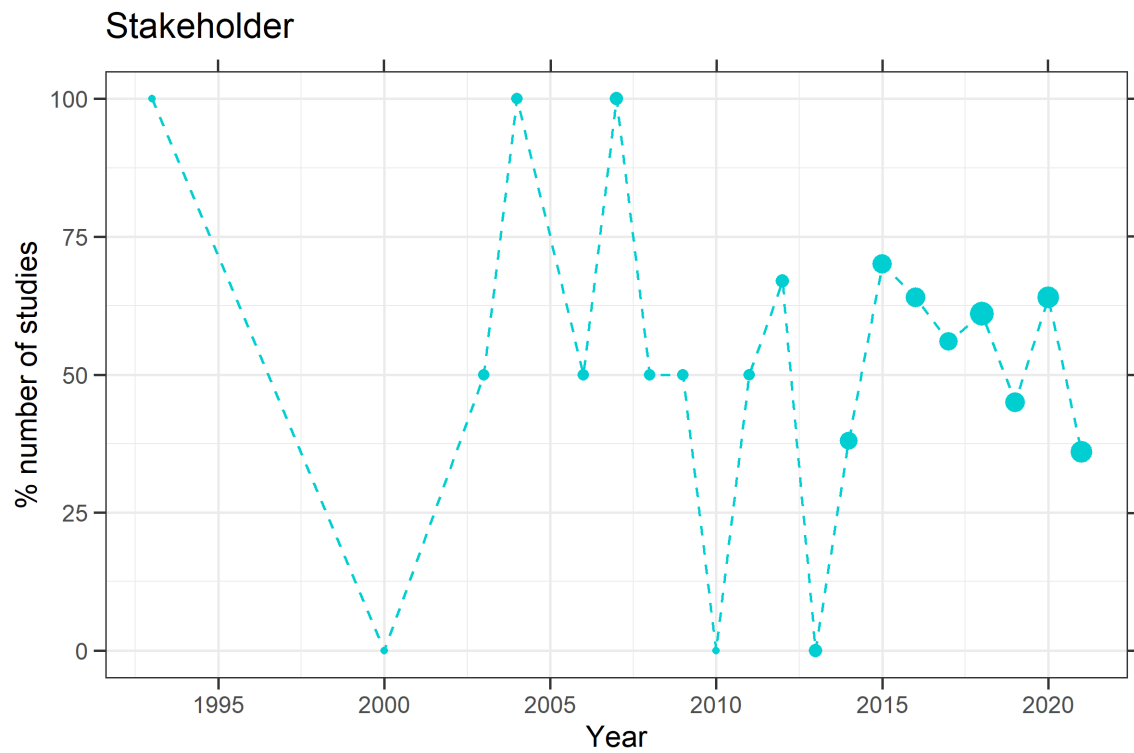


Figure 16: Whether the article included stakeholders as a function of publication date. Point size indicates the number of articles per year in the sample.

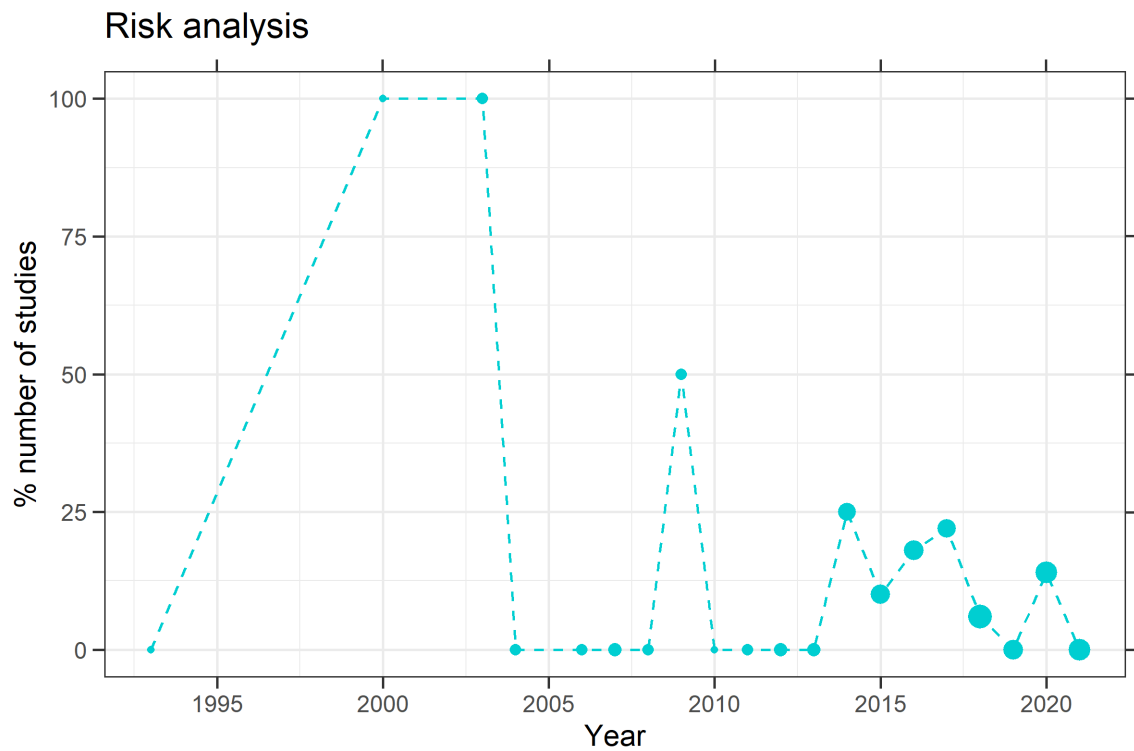


Figure 17: Whether the articles considered risk analysis as a function of publication date. Point size indicates the number of articles per year in the sample.

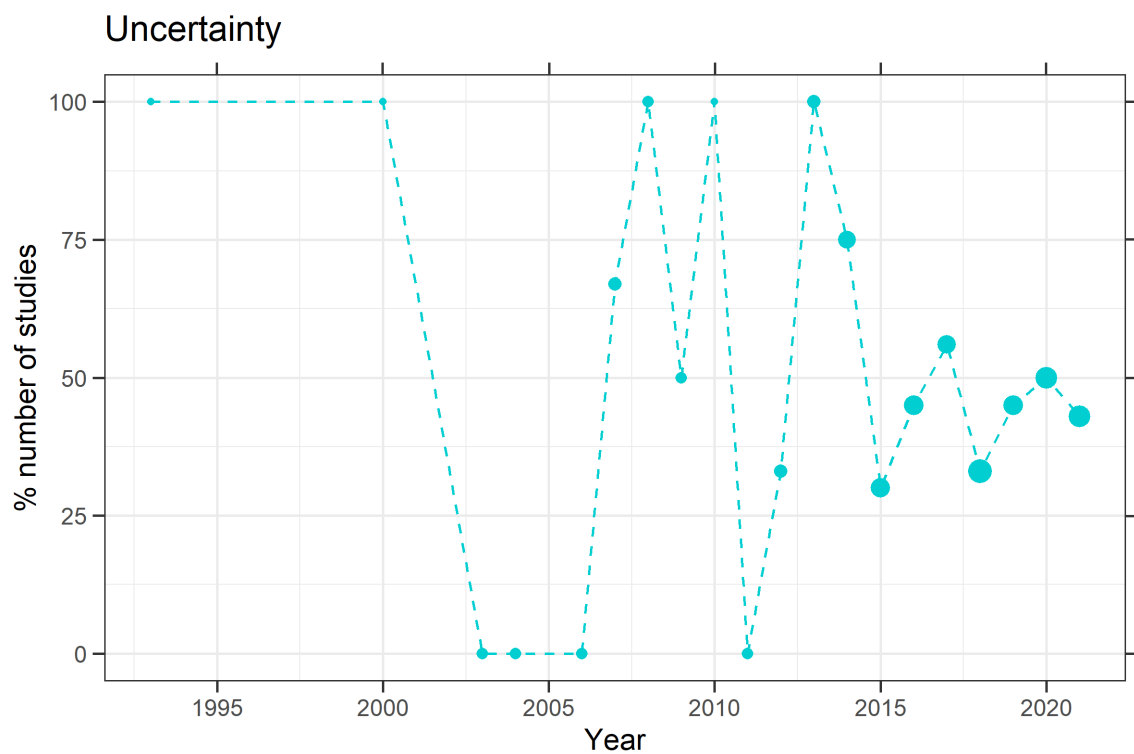


Figure 18: Whether the article acknowledged uncertainty as a function of publication date. Point size indicates the number of articles per year in the sample.

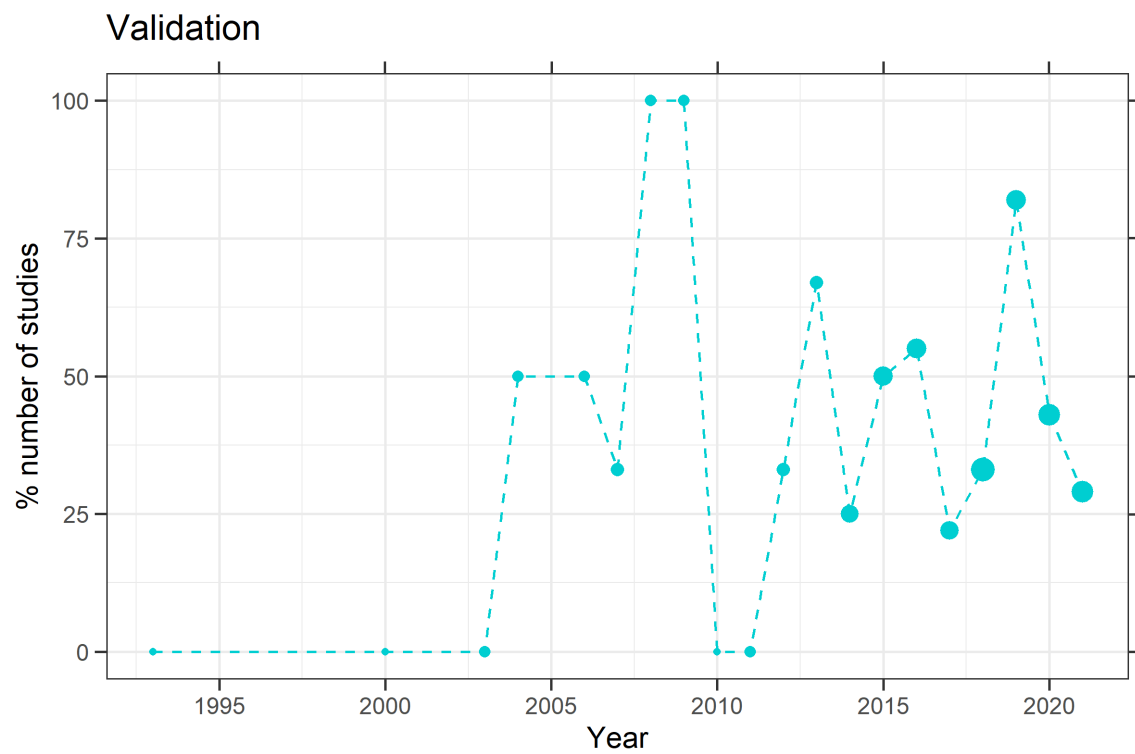


Figure 19: Whether the article performed validation as a function of publication date. Point size indicates the number of articles per year in the sample.

4 References

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