Paper title: Quantifying and reporting uncertainty in biophysical ecosystem service accounts for local policy and planning: the case of satellite-based ecosystem extent maps

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Topic our paper addresses: "Issues in Ecosystem Accounting (SEEA EA)" and the sub-topic "Accounting for physical ecosystem services".

Introduction:

As the issues of climate change and biodiversity loss become more pressing, it is essential to accurately quantify and understand land use dynamics to support effective land use policies (Cowie et al., 2018). In this context, ecosystem accounting plays a crucial role in tracking changes in ecosystem types, conditions, and services. However, the current guidelines in the System of Environmental-Economic Accounting Ecosystem Accounting (SEEA EA) do not provide any guidance on quantifying and disclosing uncertainty in ecosystem accounts (United Nations, 2022). Without quantifying uncertainty, there is a risk that policy interventions or management decisions based on ecosystem accounts leads to unintended outcomes. In this article, we address this scientific and procedural challenge by demonstrating best practices in quantifying unbiased area estimates in ecosystem extent accounts using design-based statistical methods. We use Oslo municipality in Norway as a case study to compare the effectiveness of different data sources and accounting periods in accurately estimating ecosystem extent changes. Our findings highlight the need for rigorous accuracy assessment and the development of guidelines for reporting uncertainty in ecosystem accounting.

Biophysical Ecosystem Accounting and the Importance of Uncertainty:

The absence of guidelines for quantifying uncertainty in SEEA EA may be attributed to the origin of SEEA EA as a complement to the System for National Accounts (SNA), which deals with precise transaction amounts and avoids estimation, modeling, proxy indicators, or measurement errors. Nonetheless, GDP revisions have shown notable variations (e.g., Ghana by 60%, China by 15%, Netherlands by 7%) (Barton et al., 2012) highlighting that SNA is also susceptible to uncertainty, even if it's not overtly acknowledged. In contrast to SNA, SEEA EA relies on indicators and estimation, inherently introducing uncertainty. The absence of guidelines addressing uncertainty aligns unfortunately with recent advanced national ecosystem accounts where uncertainty remains unquantified (Hein et al., 2020; Heris et al., 2021; Petersen et al., 2022). Transparently communicating accuracy and uncertainty is crucial for establishing the trustworthiness and usefulness of future ecosystem accounts (Bagstad et al., 2021; Schägner et al., 2013). The successful adoption of SEEA EA hinges on developing exemplary approaches to rigorously quantify, assess, and disclose accuracy and uncertainty – essentially, an 'uncertainty audit' tailored to ecosystem accounting.

Challenges in Ecosystem Extent Accounting:

Ecosystem extent accounts track changes in the spatial extent or area of different ecosystems over a specific period in a given area. These accounts rely on land cover maps, typically obtained from satellite-based remote sensing. The typical approach for estimating ecosystem extents from satellite-based maps is 'pixel counting', whereby the number of pixels per ecosystem type are summed and multiplied by the pixel area (Fig. 1). Although this practice is commonplace in SEEA EA, it can introduce biases in extent accounts, particularly for ecosystem conversions (Foody, 2015; Gallego, 2004). Pixel counting fails to consider classification errors and data calibration errors, leading to inaccurate extent accounts. For instance, after correcting for misclassification errors in a six-class national land cover map for the United States, Foody (2015) found that ecosystem services value changed from US$ 1118 billion yr^{-1} to US$ 600 billion yr^{-1}. Similarly, for ecosystem flows, the uncertainty inherent in satellite-based maps may exceed the ability to detect real changes in extent, particularly for certain ecosystem types. The lack of guidelines for quantifying uncertainty in extent accounts compromises the credibility of these accounts and raises questions about the reliability of ecosystem service estimates derived from them.

Design-Based Area Estimation in Ecosystem Accounting:

To overcome the limitations of pixel counting, we propose the use of design-based area estimation methods (Foody, 2013; Olofsson et al., 2014). These methods involve using satellite-based maps as a basis for stratified random sampling and creating a reference dataset through ground surveys or visual interpretation of orthophotos to classify ecosystem types and conversions (Fig. 1). Using statistical area estimators, this reference dataset is then used to calculate the area covered by each ecosystem type and quantify the uncertainty of these extent estimates. Design-based area estimation has been widely adopted in other domains, such as agriculture and forestry, to provide accurate statistics (e.g. Arévalo et al., 2020; Gallego, 2004). However, its application in ecosystem accounting has not been adequately explored. By implementing design-based area estimation in ecosystem extent accounts, we can achieve unbiased estimates and quantify the associated uncertainty.

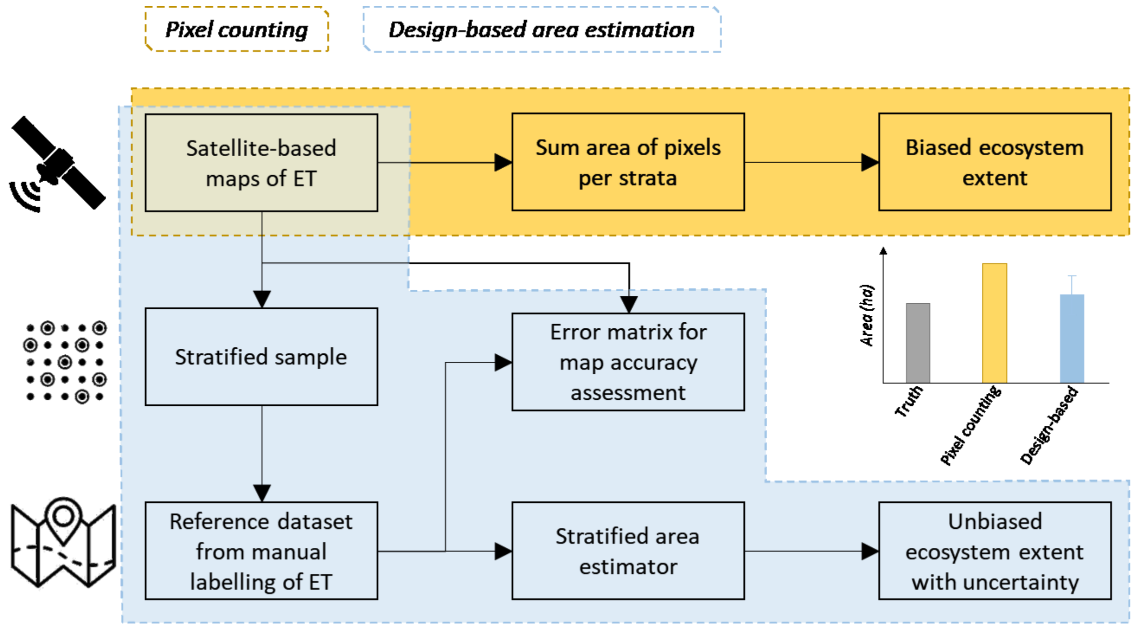

Figure 1. Workflow for deriving ecosystem extents from pixel counting methods and design-based area estimation methods. ET: ecosystem types.

Case Study: Oslo Municipality, Norway:

To illustrate the effectiveness of design-based area estimation in ecosystem accounting, we used Oslo municipality in Norway as a case study. We compared a state-of-the-art global satellite land cover map called Dynamic World (Brown et al., 2022) to compare pixel counting with design-based methods for the accounting periods 2015-2018, 2018-2021, and 2015-2021. Using design-based methods, we generated a stratified probability sample of locations based on the satellite-based maps, assigned ecosystem type labels through photointerpretation, and applied a stratified area estimator to produce 95% confidence intervals for opening, closing, and change stocks in the extent accounting tables. We found that pixel counting practices led to biased extent accounts, especially for ecosystem conversions, with biases averaging 195% of the true change value derived from design-based methods (15% bias for stable classes). Pixel counting in the 3-year accounting period produced greater bias (99%) compared to the 6-year accounting period (81%). The uncertainty in satellite-based maps was also found to exceed the ability to detect real changes for most ecosystem types. Extent accounts are shown visually in Fig. 2 and in standard accounting table format in Table 1.

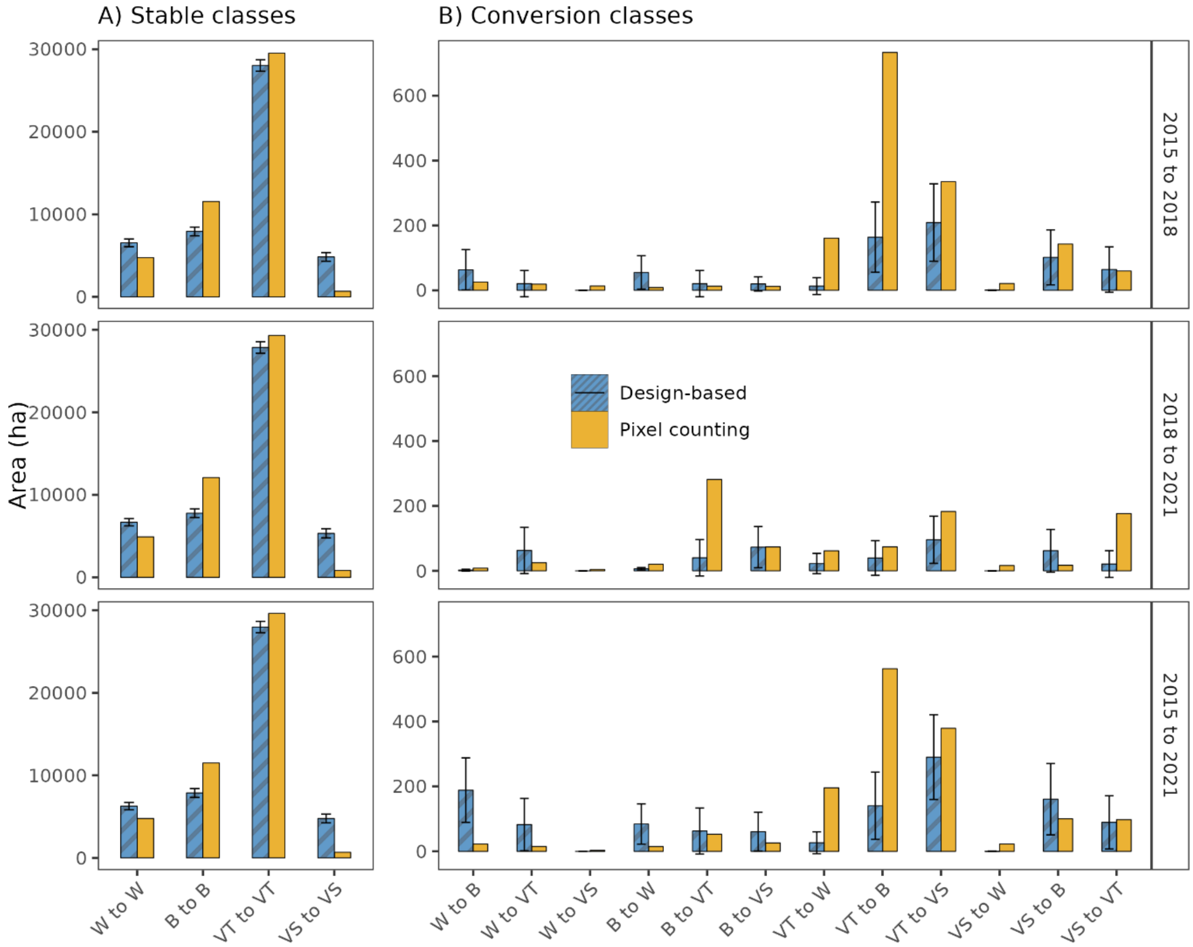

Figure 2. Area estimates for stable (A) and conversion (B) ecosystem extent classes. Design-based area estimates are provided with 95% confidence interval error bars. The accounting period and opening, change and closing stocks are presented as facetted panels. W: water; B: bare and built-up; VT: tall vegetation; VS: short vegetation.

*Table 1. Ecosystem extent accounting table for a 4-class ecosystem typology over three accounting periods. Values are expressed in hectares. Extents derived from traditional pixel counting (PC) are adjacent estimates from design-based (DB) methods which are accompanied by ± 95% CI. * PC areas which are significantly biased by exceeding the 95% CI of the DB estimates. ꜜ DB conversion estimates which reflect significant changes in ET extent (also highlighted in bold).*

		Water		Bare		Vegetation tall		Vegetation short	
		PC	DB	PC	DB	PC	DB	PC	DB
2015 to 2018	Opening	4818*	6628 ± 565	11599*	8025 ± 640	30755*	28416 ± 954	903*	5006 ± 678
	Change	132*	-15 ± 94	868*	**234 ± 166 ɫ**	-1137*	**-281 ± 186 ɫ**	137	62 ± 163
	Closing	4951*	6613 ± 541	12467*	8259 ± 781	29618*	28135 ± 852	1040*	5069 ± 663
2018 to 2021	Opening	4951*	6749 ± 513	12467*	7895 ± 650	29618*	28014 ± 849	1040*	5417 ± 654
	Change	60*	-36 ± 78	-276*	-16 ± 120	165*	-34 ± 138	51	86 ± 124
	Closing	5011*	6713 ± 474	12190*	7879 ± 648	29783*	27981 ± 860	1091*	5503 ± 684
2015 to 2021	Opening	4818*	6547 ± 624	11599*	8074 ± 723	30755*	28431 ± 967	903*	5024 ± 720
	Change	193*	**-160 ± 146 ɫ**	592*	**282 ± 212 ɫ**	-972*	**-223 ± 217 ɫ**	188	101 ± 198
	Closing	5011*	6387 ± 540	12190*	8356 ± 843	29783*	28208 ± 932	1091*	5125 ± 718

Discussion and Recommendations:

Our findings highlight the need to move away from pixel counting and adopt design-based area estimation in ecosystem accounting to ensure unbiased and accurate extent accounts. The biases introduced by pixel counting can lead to erroneous conclusions about ecosystem loss or gain. Uncertainty in extent accounts is particularly high for ecosystem conversion classes, and shorter accounting periods result in greater bias and uncertainty. We recommend that the SEEA EA community discourage the use of pixel counting unless resources for design-based estimation are limited. Instead, existing reference datasets or maps can be reused for area estimation with appropriate cross-walking and accuracy assessment. We also recommend considering simplified ecosystem typologies that can be reliably classified with remote sensing to improve accuracy and reduce uncertainty. Additionally, communication of uncertainties and limitations in extent accounts is crucial to inform policymakers and users of the accounts. Further research is needed to explore effects of spatial scale, evaluate the applicability of design-based estimation at the national level, and assess the implication of uncertainty in extent accounts on downstream ecosystem accounting processes. Perhaps most importantly, more research is needed to overcome the challenge of maintaining accounting identities with design-based area estimation methods.

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