Managing Land Subsidence in the Netherlands: A Process-Based Modelling Approach to Evaluate Alternative Sustainable Pathways

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1. Research problem & goal

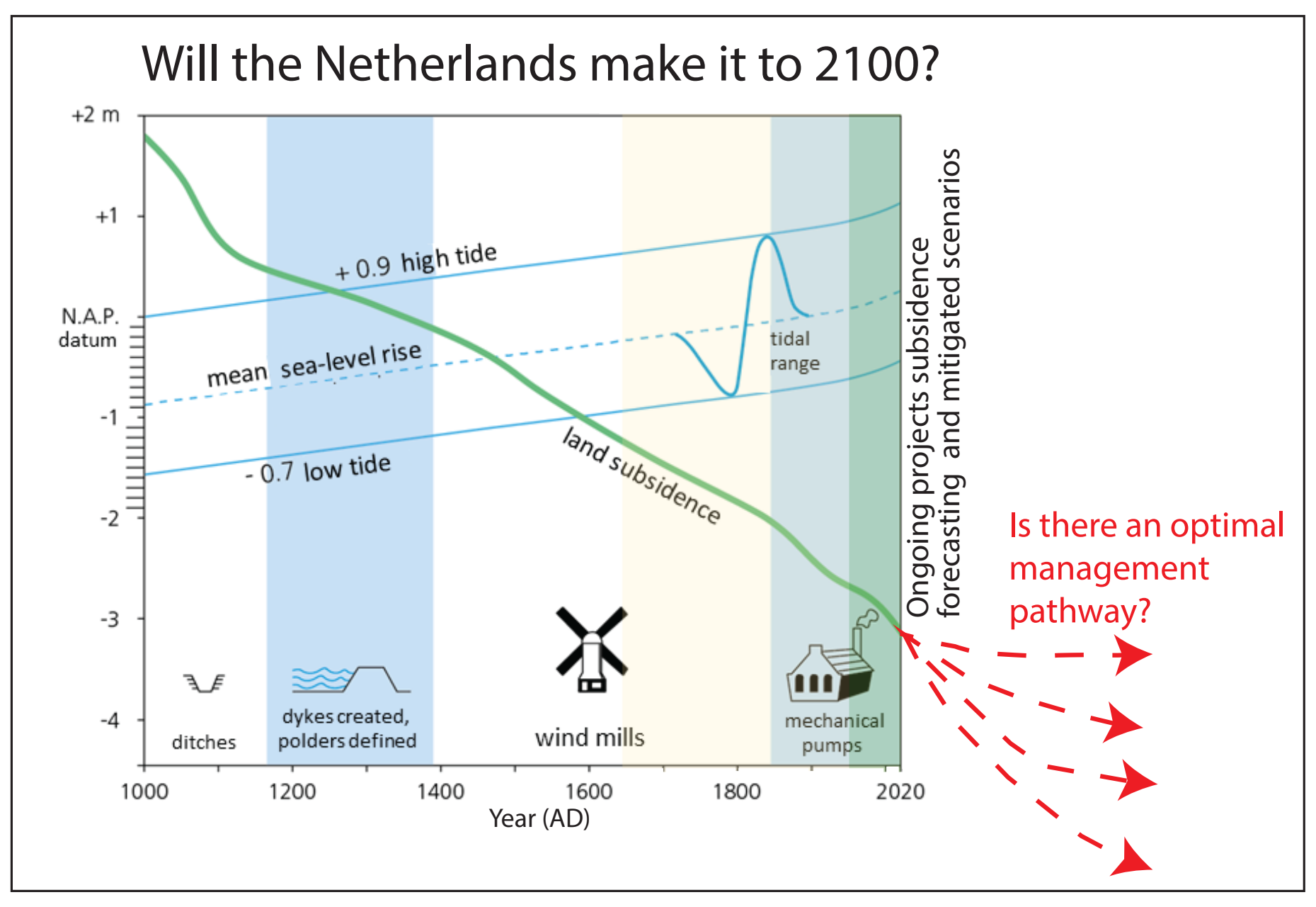

Figure 1: Centuries of land use practices and adaptation efforts have worsened the land subsidence and put the Netherlands at a precarious state (Figure adapted from Stouthamer, 2024).

- Land subsidence due to compaction of soft sediments, organic-rich peat oxidation threaten many coastal lowlands[4,16].
- While the drivers of coastal subsidence are known, it is uncertain how the future subsidence will unfold due to climate change and land use practices related uncertainties[2,6].
- In the Netherlands, the costs of land subsidence[8,19] and related GHG emissions[13] keep increasing yet there is no comprehensive adaptation/mitigation strategy in place to address them[2]. Without action, subsidence will worsen and the quality of life in soft soil areas will decrease.

- **Research question:** Can we evaluate the impact of specific mitigation and adaptation strategies against land subsidence in the Netherlands using 3D predictive modeling over a 100-year timeframe?
- **Research goal:** Assess the long-term impact of innovative mitigation and adaptation strategies on land subsidence and peat oxidation in the Netherlands through 3D predictive modeling. By the end of this study, we aim to provide valuable insights and recommendations for sustainable land management practices and policies that can help mitigate the adverse effects of subsidence in this vulnerable area.

2. The land subsidence mechanism in the Netherlands

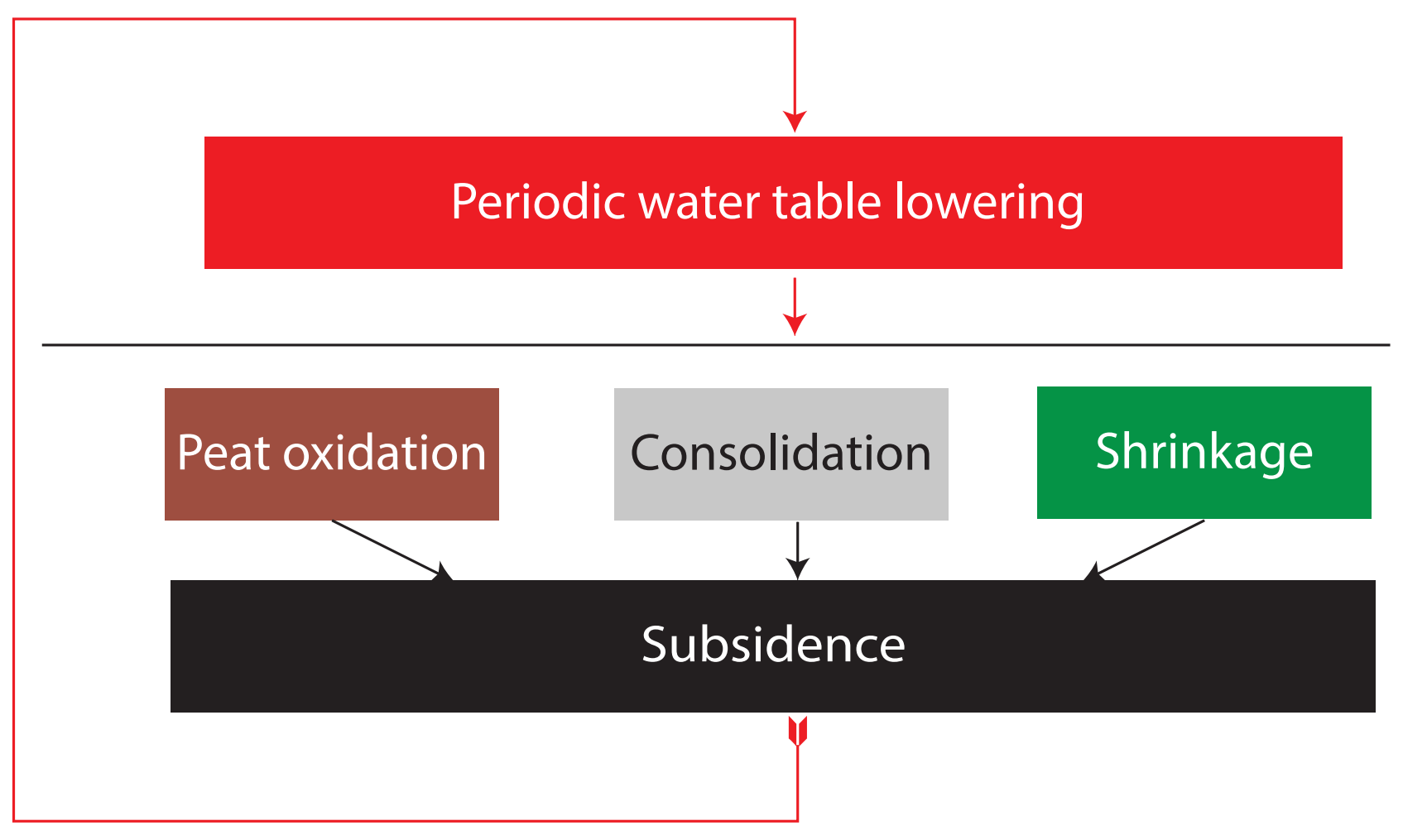

Figure 2: Periodic lowering of the groundwater level drives the land subsidence due to peat oxidation and consolidation of soil above the ground.

- The Netherlands has a history of adaptive land management by construction of canals, ditches, and drains to reclaim arable land[4,15,20].
- These adaptive measures mainly rely on periodic lowering of groundwater levels[4] (Figure 2) to sustain a certain root zone thickness by draining ditches via wind mills and mechanical pumps[15].
- Periodic lowering of groundwater levels put extensive organic-rich peat layers in contact with air, leading to peat oxidation and loss of volume[4,18].
- Increases in effective stress due to drop in pore pressures result in consolidation of sediments[10].
- Clay rich sediments undergo further shrinkage due to drying, leading to mostly irreversible consolidation[17].

3.a) Atlantis subsidence model

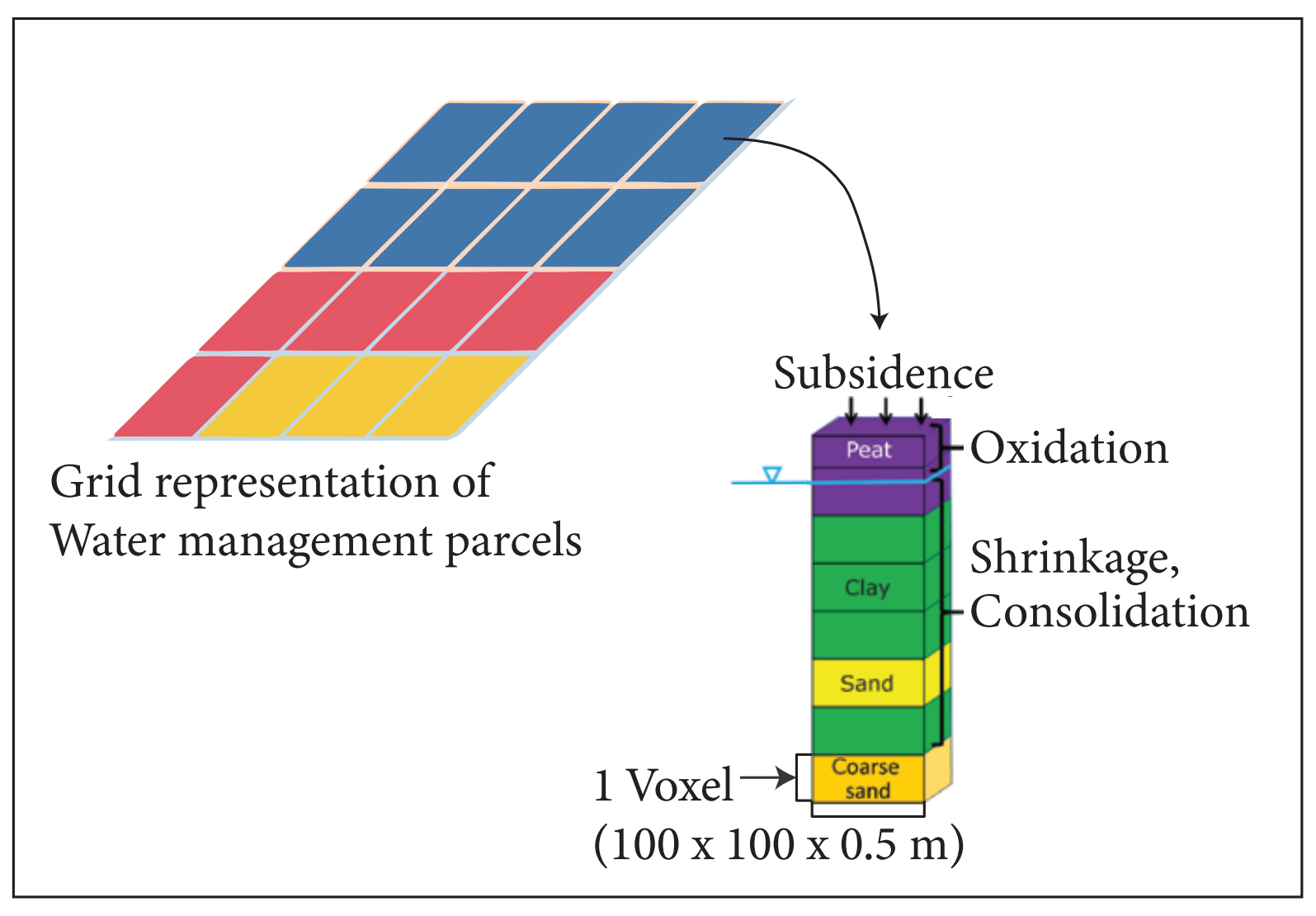

Figure 3: Representation of water management parcels and discretization of the soil column in the Atlantis model (Bootsma et al., 2020).

Atlantis[1] model quantifies key shallow land subsidence processes in the Netherlands.

Model specifications:
- Hydrostatic conditions are assumed[3].
- Consolidation based on abc-isotache concept[3].
- Peat oxidation described via an empirical relationship[3].
- Potential CO_2 emissions prediction based on method proposed by Erkens et al. (2016).

b) Scenario development

Phase 1: Forward scenarios

A set of forward scenarios was tested to quantify the extent of land subsidence potential in the upcoming century:
- water level periodic lowering
- water level fixing
- water level indexation

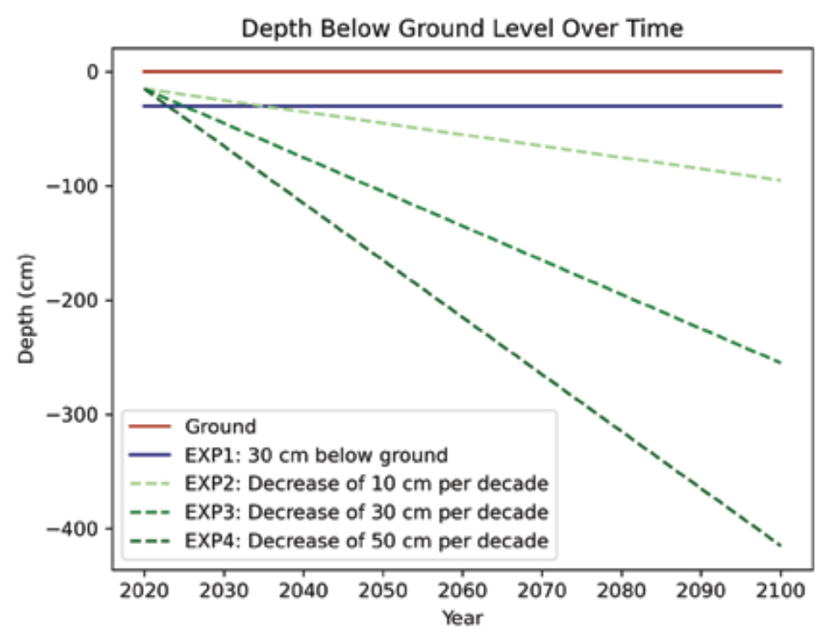

Figure 4: The set of potential water management practices that might be applied in the Netherlands.

Phase 2: Scenario based optimisation

Combining climate change predictions with land use practices in search of an optimal future land subsidence pathway.

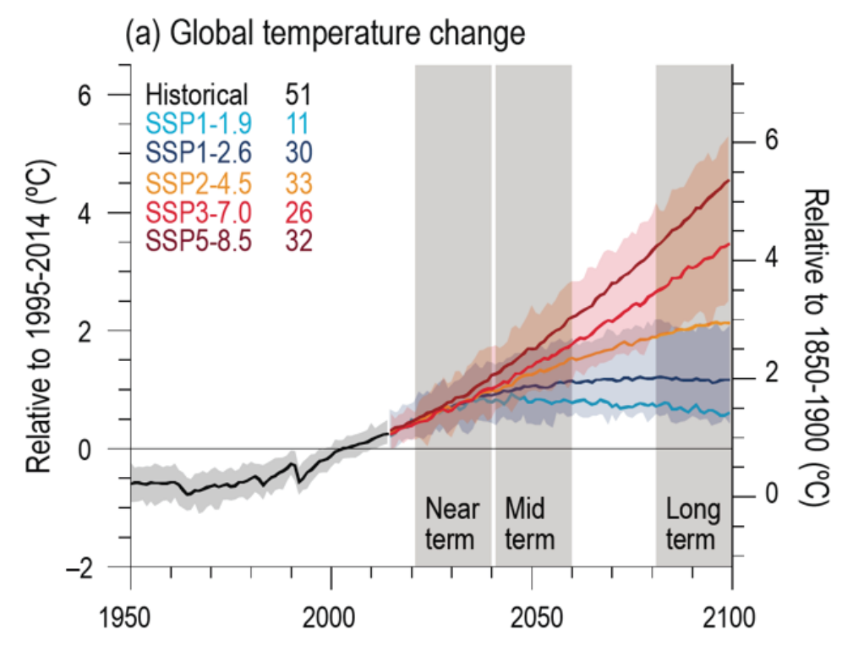

Figure 5: Adapted from Figure 4.2 in IPCC,2021: Chapter 4.[5] Predicted "Global surface air temperature changes relative to 1995-2014 average (left axis)".

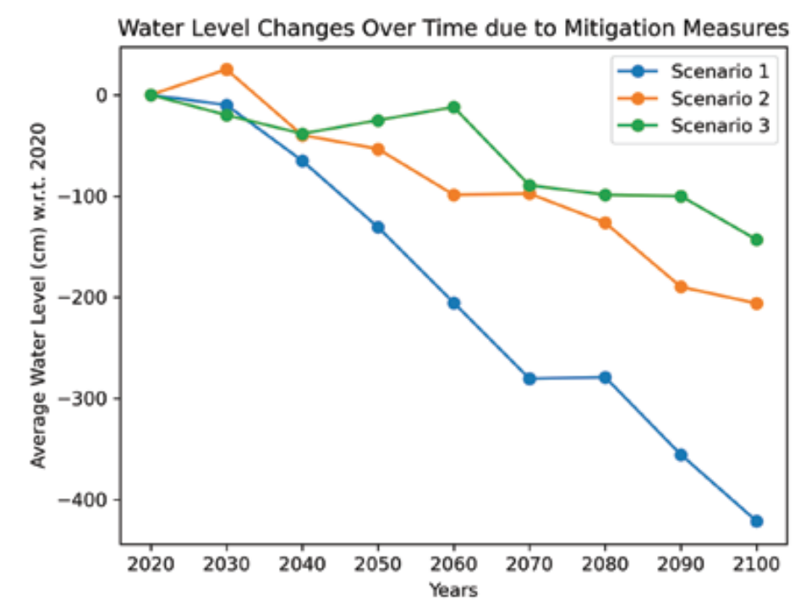

Figure 6: Potential changes in the water level as a result of land subsidence mitigation efforts and land use practices in the Netherlands.

c) Data

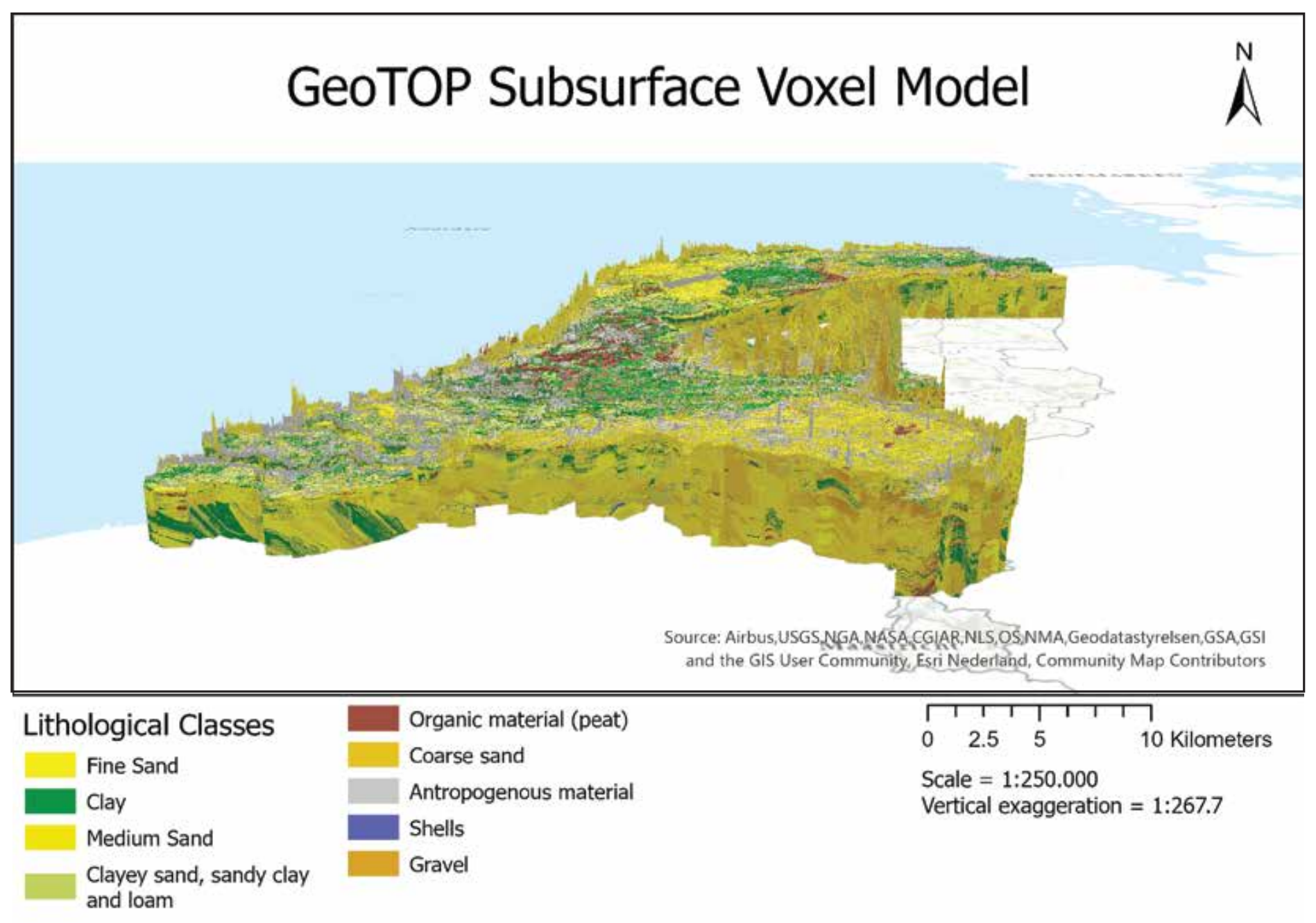

Figure 7: 3D lithological voxel model of the subsurface of the Netherlands up to 50m depth at 100-100-0.5m (X-Y-Z) resolution (TNO-GSN).

- The top 1.2 meters of the soil column was defined using the BRO Bodemkaart dataset[3].
- Soil column description from 1.2 meters to 30 meter depth were defined using the TNO GeoTOPv1.4 model[15] and NL3D[3].
- The mean yearly minimum water level (GLG) from 2020 was imposed at hydrostatic conditions.
- Surface elevation data: AHN3[3].
- Climate change scenarios were based on a strong climate change impact from KNMI'14 predictions[3,7].

4. Preliminary results from forward scenarios

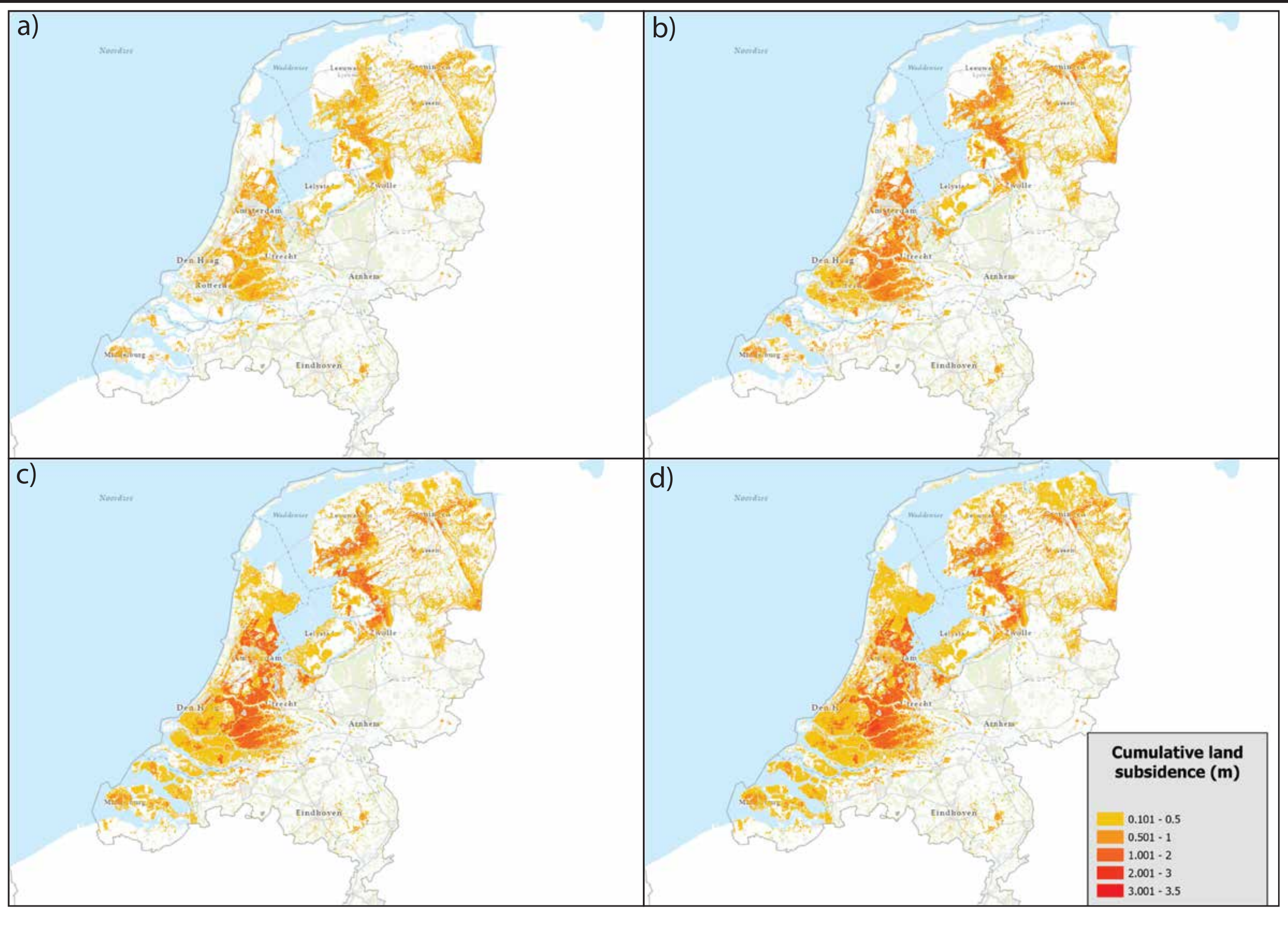

Figure 8: Land subsidence predictions up to 2100 due to peat oxidation and consolidation in the case of a) groundwater level fixing (EXP1); periodic groundwater level lowering b) by 10 cm per decade (EXP2), c) by 30 cm per decade (EXP3), d) by 50 cm per decade (EXP4).

Forward scenarios based on potential water management practices indicate and confirm that:
- Fixing water level w.r.t. ground level at 2020 (EXP1) limits the subsidence to shallow peat and clay areas in the northern and western Netherlands.
- Periodic water level lowering (EXP 2,3,4 shown in Figure 4) progressively worsens the land subsidence.
- Particularly, peat areas suffer the largest subsidence primarily due to peat oxidation.

5. From land subsidence to spatial impact predictions

Using the land subsidence predictions as an input to damage risk algorithms for impact estimation.

Urban

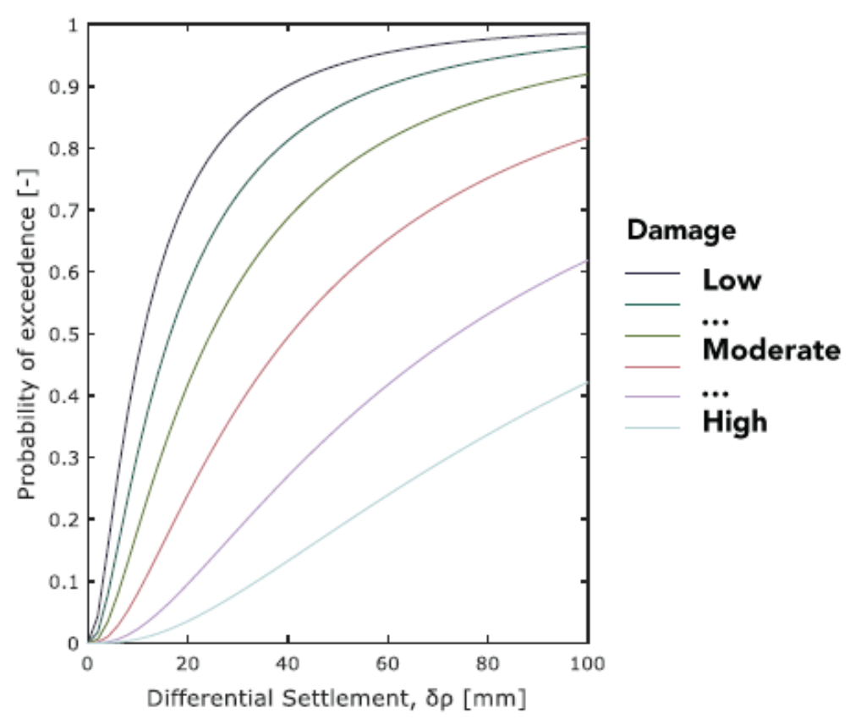

Figure 9: Empirical Fragilty Curves (EFC) proposed by Prosperi et al., (2023) to quantify urban land subsidence related costs (Figure from Prosperi et al., 2024).

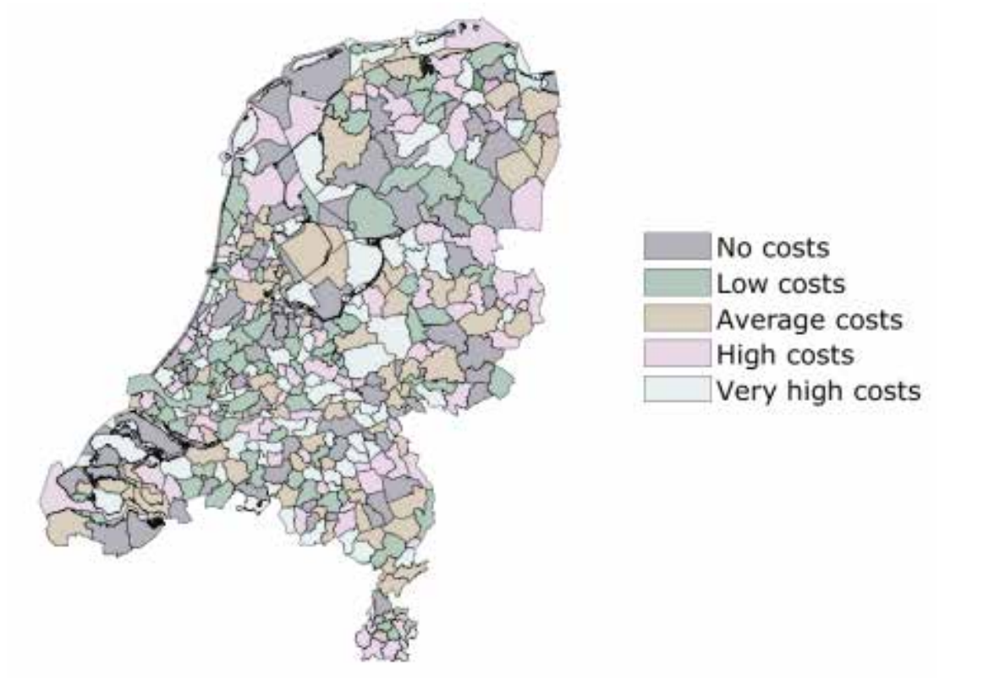

Figure 10: Combining land subsidence with EFCs can allow us to predict the impact of subsidence in urban areas for the Netherlands (Figure from Prosperi et al., 2024).

Rural

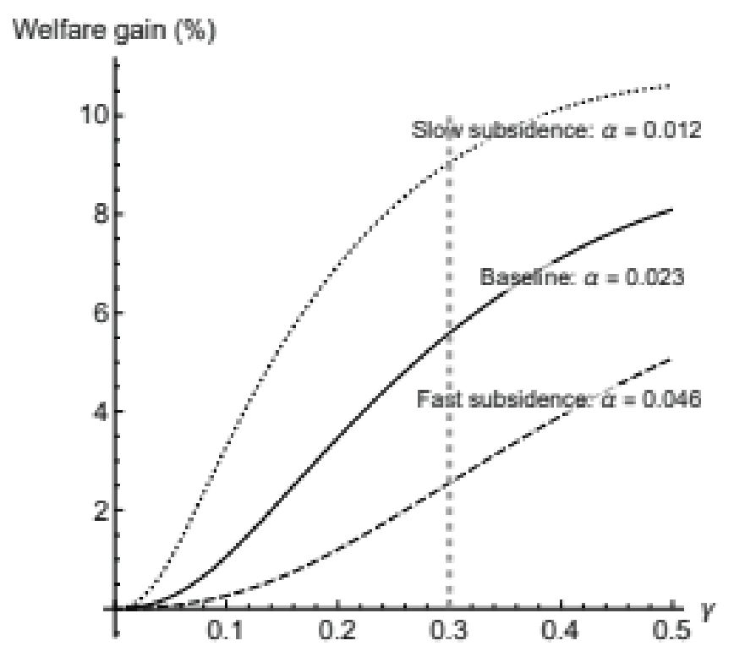

Figure 11: Optimal Control Model (OCM) proposed by Sen et al., (2023) to quantify rural grassland related costs (Figure from Sen et al., 2023).

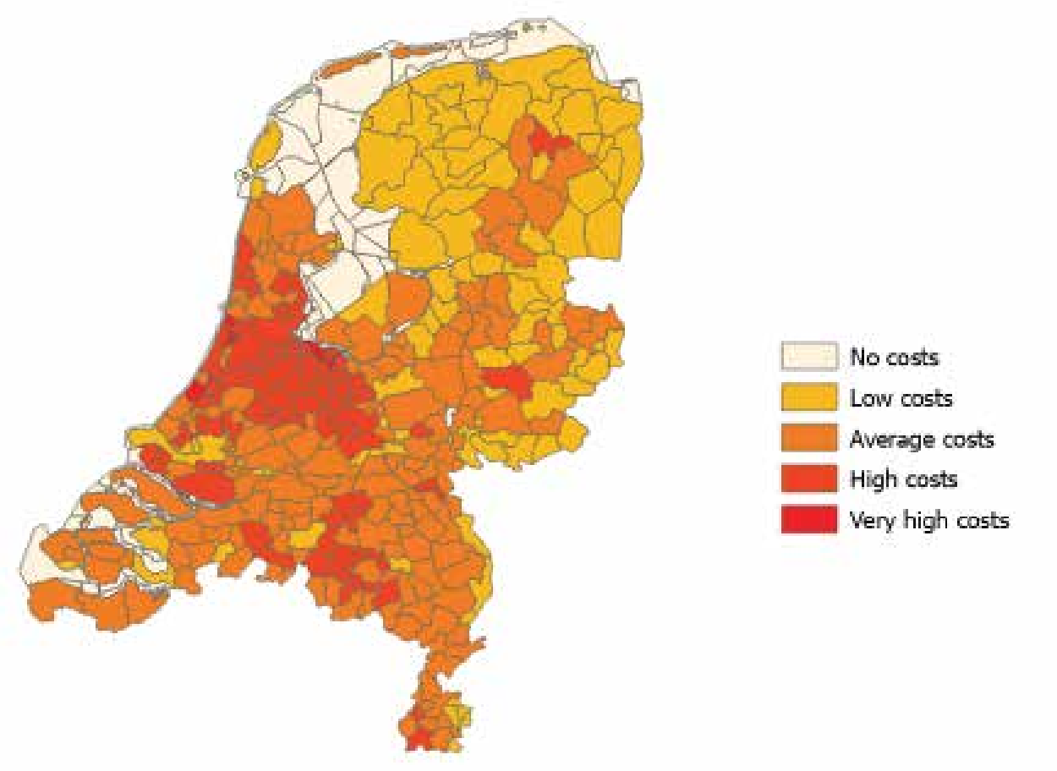

Figure 12: A hypothetical example of spatial rural risk assessment by combining land subsidence predictions from Atlantis and OCM for the Netherlands.

6. References and acknowledgement

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