

1 Economic incentives for raising coastal 2 flood defenses in Europe

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16 Extreme sea levels (ESLs) in Europe could rise by as much as one meter or more due to climate change by
17 the end of this century¹. Without adaptation measures, annual damages from coastal flooding in Europe
18 could increase sharply from €1.4 billion nowadays to at least €90 billion by 2100². While damages will be
19 lower than those figures as countries continue to protect their coast, there has been no dedicated
20 European cost-benefit analysis of possible protective measures against rising seas. Here we present a first
21 comprehensive analysis of economically efficient adaptation scenarios for Europe during the present
22 century. We employ a fully probabilistic framework considering all major sources of uncertainty, as well as
23 dynamic simulations of all future ESL components and inundation. We find that at least 83% of flood
24 damages could be avoided by elevating dykes in an economically efficient way along the European
25 coastline. This corresponds to 23.7%-32.1% of Europe's coastline, specifically where high value
26 conurbations exist. The mean benefit to cost ratio of such investment varies from 6.7 to 14.9, depending on
27 the scenario and can even reach 30 for high-end greenhouse gas emission and socio-economic projections.

28

29 The coastal zone is an area of high interest. At present, more than 200 million European citizens live within 50 km
30 from the coastline, stretching from the North-East Atlantic and the Baltic to the Mediterranean and Black Sea, and
31 current trends indicate that migration toward coastal zones is continuing^{3,4}. Coastal areas host important commercial
32 activities and also support diverse ecosystems that provide important habitats and sources of food⁵. Coastal zones
33 are particularly vulnerable to climate change due to the combined effects of sea level rise and potential changes in

34 the frequency and intensity of storms^{6,7}. Global mean sea level has increased by 13-20 cm since pre-industrial times⁸.
35 This process has accelerated since the 1990s^{9,10} due to global warming⁹. This has already contributed to coastal
36 recession^{10,11} and made Europe's coasts more susceptible to coastal hazards. The continued rise in sea levels along
37 Europe's coastlines in view of global warming could result in unprecedented coastal flood losses in Europe in case no
38 additional coastal protection and risk-reduction measures are implemented².

39 There exists a range of possible adaptation measures to increase the resilience of future coastal societies to flooding¹².
40 These include natural (dunes) and artificial (dykes) structures, beach nourishment, forecasting and warning systems,
41 flood proofing of infrastructures, and retreat from high-risk areas^{13,14}. Nature-based solutions have recently gained
42 attention as more environmentally sustainable ways to protect and maintain coastlines¹⁵. Among the various
43 adaptation options, hard protection is the strategy that delivers the most predictable levels of safety against coastal
44 extremes and sea level rise and applied widely especially along developed coastlines like those of large parts of
45 Europe¹⁶. Dyke or seawall reinforcement, in particular, has been the most common practice for decades, despite the
46 fact that hard protection can affect the landscape in a negative way, increase erosion, reduce amenity value and result
47 in more catastrophic events in the case of failure¹⁷. A possible alternative strategy is relocating dwellings and
48 infrastructure in order to reduce coastal flood risk¹⁸, but relocation is often challenging to implement due to technical
49 issues such as (e.g. moving critical infrastructure such as ports of power plants) or public opposition¹⁹.

50 For these reasons, we evaluate the costs and benefits of applying additional protection through dyke improvements
51 along the European coastline, assuming that the densely populated and high income European coastal communities
52 will choose to 'hold the line'. We employ a probabilistic data and modelling framework, that includes the following
53 steps: (i) estimate present and future extreme sea levels along Europe's coastlines based on state-of-the-art
54 projections of sea level rise, waves, storm surges and tides for a high emissions (RCP8.5) and moderate emissions
55 (RCP4.5) ¹ pathway; (ii) delineate the land areas inundated when extreme sea levels overtop current coastal protection
56 and derive the corresponding flood inundation depth using 2-D hydraulic modelling²⁰; (iii) overlay the inundation maps
57 with exposure information on population and land use; (iv) translate this into direct flood losses using functions that
58 relate the depth of inundation with economic damage to the assets inundated, and into the number of people flooded,
59 taking into account gridded socio-economic projections³, according to the Shared Socioeconomic Pathways (SSPs;
60 expressing changes in asset values and level of urbanization in the future)²¹; (v) follow the same approach to assess
61 European river flood risk²², repeat steps (ii-iv) with step-wise increases in dyke height and compute economic benefits
62 (= avoided flood damage during this century) and dyke cost based on unit costs taken from the literature; (vii) finally,
63 for each coastal segment the dyke height that maximizes the net present value (NPV), which is the discounted sum of
64 the dyke cost (negative) and the economic benefits (positive) over the project lifetime, is considered the optimum.
65 Dyke costs include construction investment and maintenance costs. Benefits are the avoided losses from coastal
66 flooding from 2020 up to the end of this century. We applied a discount rate of 5% for the EU cohesion countries and
67 3% for the other EU member states.

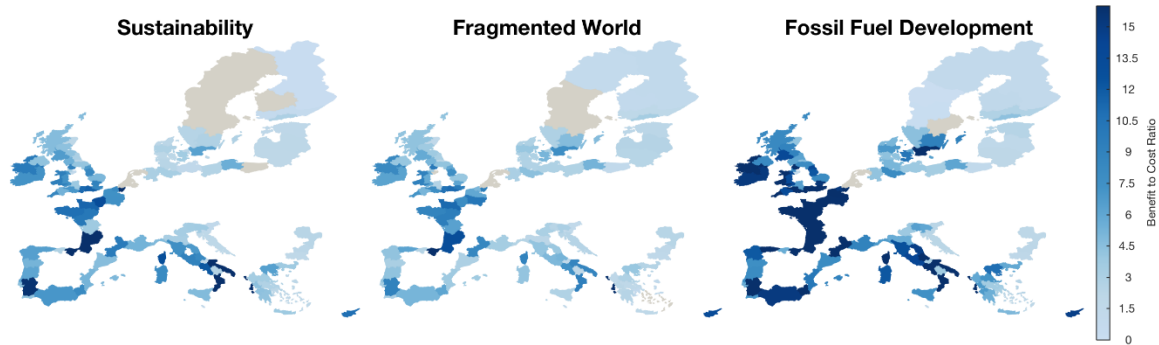
68 All variables computed in this study are available as probability density functions, but we focus our discussion mainly
69 on the expected values, as well as on the very likely range, represented by the 5th-95th quantiles. The CBA considers
70 the uncertainty range of damages and costs. Results are presented and discussed at four spatial scales: along ~10,000
71 coastal sections of the European coastline, as well as at NUTS2, country and European level. We assess the following
72 three scenarios: i) Sustainability combining moderate emissions with SSP1 which represents global sustainable
73 development; ii) Fragmented World combining high emissions with SSP3, and iii) Fossil Fuel Development combining high
74 emissions with SSP5²¹. The highest increase in GDP and population is projected under Fossil Fuel Development,
75 reaching by the end of the century values which are 10 and 2 times higher than the baseline, respectively. Population
76 in 2100 is similar to the baseline under Sustainability, while GDP is almost triple. Under Fragmented it is GDP that
77 changes very little and the 2100 population increases by at least 30%.

78 The European average 100-year ESL is projected to show a very likely increase of 34–76 cm under a moderate-
79 emission-mitigation-policy scenario and of 58–172 cm under a high emissions scenario. The above increase is similar
80 to the one projected for the mean sea level at European level. The biggest ESL increase is projected for the North Sea,
81 due to increasing meteorological contributions, while the contrary applies for the northern Baltic Sea; due to land
82 uplift. The Atlantic coast of Spain and Portugal is also projected to experience a lower increase in extreme sea levels,
83 due to milder storms²³.

84 At present, coastal flood losses in Europe amount to €1.4 billion/year (all values are expressed in 2015 € values), and
 85 each year about 100,000 EU citizens are affected from coastal flooding. Flood risk is projected to increase strongly in
 86 Europe with global warming. In the absence of further investments in coastal adaptation and under the Sustainability
 87 scenario, annual coastal flood losses for Europe by the end of the century are projected to grow to €209.8 billion
 88 around a very likely range from €29.7 billion to €844.5 billion (Table 1). Similar estimates under Fragmented world
 89 and Fossil fuel based development are €121 billion (14.9-481.6), and €1268.4 billion (160.9-4,731.1). During the same
 90 time span, the total number of people flooded in Europe is projected to rise to 1.61 (0.5-3.1), 1.59 (0.5-2.8) and 3.9
 91 million (3.9-6.9), respectively (Table 2). Coastal flood risk will increase in all EU-countries that have a coastline, with
 92 France, the UK, Italy and Denmark showing the highest absolute increase in coastal flood risks towards the end of the
 93 century. For some countries, coastal flood losses at the end of this century could amount to a considerable share of
 94 their GDP, especially under a high-emissions pathway (RCP8.5), most notable in Cyprus (4.9%), Greece (3.2%),
 95 Denmark (2.5%), Ireland (1.8%) and Croatia (1.8%).

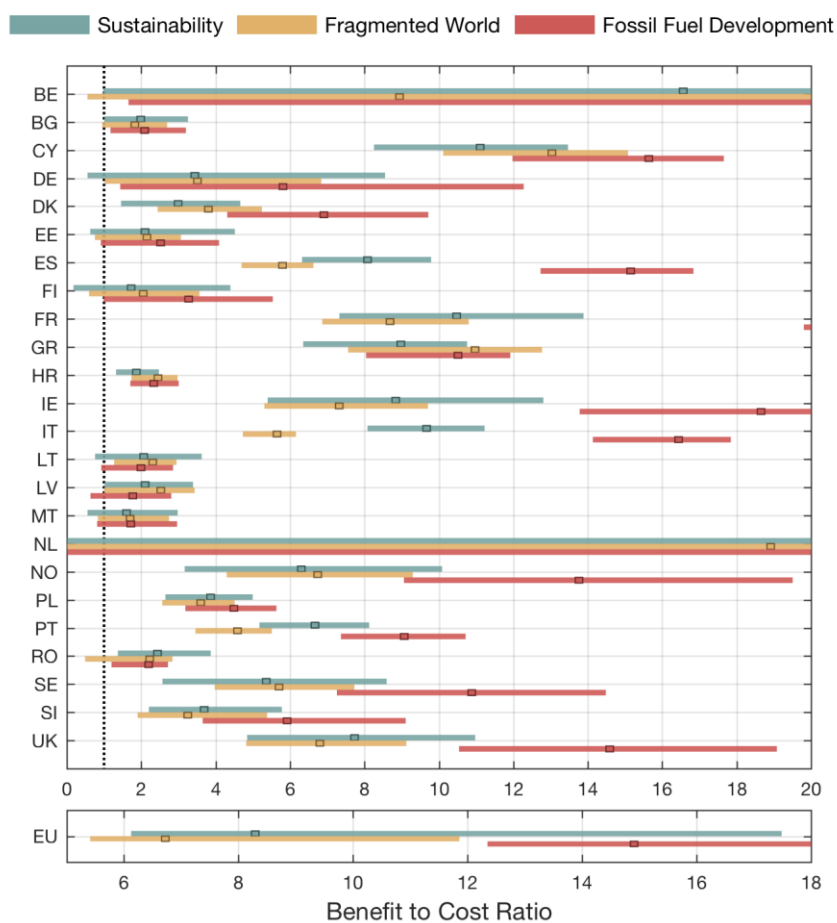
96 While those numbers illustrate the large adaptation needs Europe is facing, the underlying assumption of no further
 97 investment in coastal protection is not very plausible given such high relative losses. Conversely, where human life
 98 may be at risk and high density, high value conurbations exist, it is very likely that the use of hard defense structures
 99 will continue. The Benefit to Cost Ratio (BCR) of increased protection, however, varies strongly across Europe. Costs
 100 outweigh benefits for 76% of the European coastline, under Sustainability and Fragmented world (likely range 76%-
 101 89%), and for 68% under Fossil fuel based development (67%-81%; Table 3). This implies that there is no economic
 102 motivation for further protecting these areas. Low BCR can be related to several factors, like steep morphology and
 103 sparsely populated coastlines, such as in Greece and Malta. Also, long and complex coastlines imply higher dyke
 104 construction costs, hence lower BCR, such as in many parts of Finland, Sweden, Estonia, and Croatia. Most of the
 105 Baltic is experiencing uplift and therefore relative sea level rise is lower compared to other parts of Europe, implying
 106 lower future losses and hence potential benefits of adaptation for a significant part of Finland and Sweden.

107 Despite the absence of economic incentives to adapt along a high percentage of the European coastline, the
 108 concentration of human development renders adaptation very economically beneficial in certain areas. Benefits tend
 109 to outweigh costs in areas where population density is larger than 500 people per km². In urbanized and economically
 110 important areas the benefits tend to exceed the costs by at least an order of magnitude. As a result, when benefits
 111 and costs are aggregated at regional level, the total benefits are dominated by those in urban centers and this
 112 compensates for the low BCR in less densely populated and rural coastal stretches. At NUTS2 level, adaptation appears
 113 as economically efficient (BCR > 1) in about 82%, 84% and 86% of the regions, under Sustainability, Fragmented world
 114 and Fossil fuel based development, respectively. Adaptation comes with far stronger economic benefits in Devon
 115 (mean BCR equal to 14, 11 and 60, respectively), Puglia (17, 8 and 49), Murcia (15, 8, 37), Loire (8, 7, 44), East Anglia
 116 (9, 10, and 44), Languedoc-Roussillon (10, 6, and 42), Merseyside (15, 10 and 31), and Basque country (13, 8 and 33)
 117 (Figure 1).



118
 119 Figure 1. Mean benefit to cost ratios per NUTS2 region under Sustainability, Fragmented world and Fossil fuel based
 120 development. Grey colors express areas where the maximum Net Present Value is achieved with the protection already in place.
 121

122 At country level, Belgium is the country with the highest percentage of coastline where benefits exceed costs (85%-
 123 95% depending on the scenario), followed by France (57%-66%), and Italy (44%-59%; Table 3). These are also the
 124 countries with some of the highest expected BCRs, varying within 8.9-25.8, 8.7-24.8, and 5.6-16.4, respectively (range
 125 expresses variation among scenarios; Figure 2). Other countries with high BCR values are the Netherlands (Expected
 126 BCR between 18.9 and 34.3), Cyprus (11.1-15.6), Ireland (7.3 and 18.7), and Greece (9-11) (Figure 2 and Table 3). On
 127 the lower end of the analysis is Malta, for which the expected country level BCR is the lowest in Europe: 1.6-1.7,
 128 depending on the scenario. Other countries with low BCR values are Bulgaria (expected BCR equal to 1.8-2.1),
 129 Lithuania (2-2.3), Latvia (1.8-2.5) and Croatia (1.9-2.4). Overall, BCRs under Sustainability and Fragmented world are
 130 rather similar, as the higher GDPs under the former compensate the higher seas under the latter. Since Fossil fuel
 131 based development combines strong increase in ESLs with socio-economic growth, the resulting BCRs are higher, for
 132 some countries more than double compared to the other scenarios (e.g. France, Ireland, Sweden, Denmark, and
 133 Finland (Figure 2 and Table 3). The mean expected BCR for Europe is 8.3 (likely range: 6.1-17.5), 6.7 (5.4-11.9) and
 134 14.9 (12.3-29.6), under Sustainability, Fragmented world and Fossil fuel based development, respectively (Figure 2).
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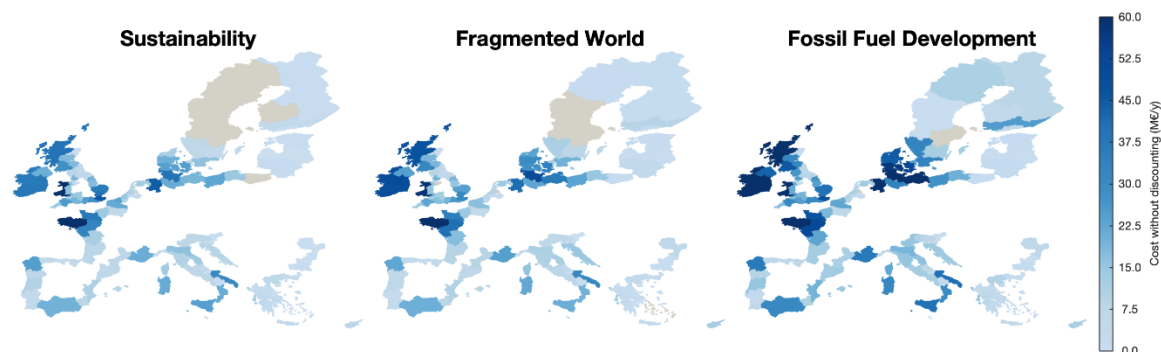


136
 137 Figure 2. Benefit to cost ratios per country. Each color expresses a scenario (Sustainability (green), Fragmented world (orange)
 138 and Fossil fuel based development (red)), with patches expressing the very likely range and squares the mean. The vertical black
 139 dotted line expresses BCR=1.

140
 141 The Netherlands is a particular case as the country is already very well protected (up to ~10,000 year return period),
 142 by an extensive network of dykes and surge barriers. We find that with additional protection it is even less likely that
 143 the Netherlands will experience a catastrophic flood during the century. However, the country has a high income

144 level, an extensive low-lying area and high population density, so flood events can have massive impacts when they
 145 occur, and for that reason the mean BCR for the Netherlands is the highest in Europe. Thus, the benefits from
 146 protecting further are high (high mean BCR), even though flood events are rare; explaining the high uncertainty in the
 147 BCRs (Figure 2, similar for Belgium): among the 10,000 extreme sea level scenarios simulated in the stochastic
 148 approach, few included catastrophic floods during the century, resulting in high losses. These rare but high impact
 149 events lead to the high BCRs. On the contrary, many realizations of future extreme sea levels do not surpass the
 150 present high protection standards, hence flood risk is very low, or even zero in the case of the Netherlands, and so is
 151 the low-end BCR.

152



153

154 Figure 3. Expected annual undiscounted costs of adaptation per NUTS2 region, under Sustainability, Fragmented world and Fossil
 155 fuel based development (million €/year). Colors express the mean annual value averaged through the entire century.

156

157 The expected annual investment on further dyke improvements during the present century, under Sustainability and
 158 without discounting, is €1.75 billion/year, around a very likely range of €1.75–€7.39 (Table 4 and Figure 3). Similar
 159 estimates for Fragmented world and Fossil fuel based development are €1.87 (€1.87–€7.88) and €2.82 (€2.82–€11.89)
 160 billion/year, respectively. Country level adaptation costs are mainly controlled by the value of assets and the coastline
 161 length, with the UK (€478-719 million/year), France (€288-385 million/year), Norway (€126-296 million/year), Italy
 162 (€168-261 million/year), and Germany (€125-230 million/year) facing the highest projected costs (Table 4). Other
 163 countries with substantial costs of dyke reinforcement are Denmark, Ireland, Spain and the Netherlands (>€50
 164 million/year under all scenarios), as well as Sweden, Poland, Greece, Portugal and Belgium (all above €20 million/year
 165 under all scenarios).

166 Considering only the locations where further protection is needed, the additional average coastal defense height
 167 needed in Europe is 92, 95 and 104 cm under Sustainability, Fragmented world and Fossil fuel based development,
 168 respectively (Table 4). Country average values vary from a minimum of 31-39 cm (Malta) to a maximum of 2.23-3.43
 169 m (Belgium), with the range expressing the uncertainty among scenarios. Apart from Belgium, other countries that
 170 need to apply substantial additional protection are Slovenia (1.72-2.32 m), Poland (1.57-1.66 m), UK (1.39-1.5 m),
 171 Germany (1.33-1.42 m), the Netherlands (1.3-1.53 m), Latvia (0.83-1.41 m), and Estonia (0.97 and 1.42 m).

172 Applying adaptation that optimizes NPV of coastal protection everywhere along the European coastline would still
 173 result in losses from coastal flooding, especially towards the end of the century. By 2100, EU total EAD will reach €8.8,
 174 €21 and €24 billion under Sustainability, Fragmented world and Fossil fuel based development, respectively (Table 5).
 175 However, these represent a 96% (€200.1 billion), 83% (€100 billion) and 98% (€1.24 trillion) reduction compared to a
 176 do-nothing scenario. The highest losses are projected for Scotland, Ireland, Denmark, Romania, Croatia, Cyprus, Sicily,
 177 Andalucía, Bretagne, the south east Baltic Sea, and Provence, with NUTS2 level EAD exceeding €300 million towards
 178 the end of the century under Fossil Fuel Development (Table 5).

179 Similarly, further coastal protection will still result in people flooded with the EU total expected annual number of
 180 people flooded (EAPF) towards the end of the century reaching 653.4k, 786.9k and 1343.1k under Sustainability,

181 Fragmented world and Fossil fuel based development, respectively (Table 5). Still the additional protection will reduce
182 the 2100 EAPF along the entire European coastline by 59% (959.2k people), 51% (807k people) and 66% (2555.1k),
183 respectively, compared to a 'do nothing' scenario (Table 5). The population around the Puglia, Croatia, the Ionian
184 Islands, the Basque country, Basse Normandie, Nord Pas de Calais, Scotland, Ireland and south east UK are projected
185 to be more affected by coastal floods, with NUTS2 level EAPF exceeding 15,000 towards the end of the century under
186 Fossil fuel based development (Table 5).

187 The present analysis has shortcomings that are inherent to the scale of the application. We note that in our cost-
188 benefit analysis the benefits are limited to avoided flood risk until the end of the 21st century. Other potential costs
189 of increased protection of coastal areas against inundation, such as the loss of valuable ecosystems through coastal
190 squeeze²⁴, are not included in the analysis.

191 Near river deltas and estuaries coastal and river flooding could coincide. Such compound events could reinforce each
192 other and give rise to impacts that are larger than the sum of the impacts of the single events. With rising extreme
193 sea levels along Europe's coastlines and increasing river flood hazard in many parts of Europe, compound flood hazard
194 will likely increase in Europe²⁵. A proper assessment of this hazard and the consequent risk is yet lacking at continental
195 scale, it should be noted, however, that to date compound flood risk represents only a marginal fraction of the total
196 flood risk in Europe²⁶.

197 Sea levels are projected to increase long after 2100 and very likely this will happen at an accelerating rate^{27,28}. Hence,
198 even though our impact and cost-benefit analysis is limited until 2100, adaptive measures taken now will also lower
199 flood risk during the 22nd century and beyond. Considering longer time spans, the benefits and maintenance costs of
200 rising dyke heights are therefore likely much higher than estimated in this paper.

201 This study focusses only on the costs and benefits of further dyke improvements. Nature-based solutions have shown
202 capacity to mitigate erosion and flood risk under current sea levels, yet there is no solid evidence about their
203 effectiveness to protect European coastal communities against the expected rise in sea level extremes¹⁶, that could
204 be up to one meter or more. However, this does not exclude the parallel implementation of more sustainable
205 environmental practices to enforce the physical and ecological resilience of coastal zones.

206 The probabilistic framework that we applied allows decision makers to interpret the results according to the amount
207 of risk they consider as acceptable. Our projections of future coastal hazard and risk, as well as dyke costs, come with
208 uncertainty, and in this report we evaluated the adaptation option that optimizes the expected benefits vs costs
209 However, stakeholders could select a more conservative criterion and optimize adaptation investments in view of
210 high-end, less probable future scenarios, under which flood impacts will be higher, instead of the whole range
211 currently considered. Such a choice would result in higher adaptation costs, but would also imply lower risks for future
212 generations, as the analysis would prioritize protection against the rarer and more catastrophic events.

213 The use of discounting is another critical aspect as high discount rates put more weight on short term costs and
214 benefits. Here this means that capital investment costs in protection, which occur now, are emphasized, while future
215 benefits of adaptation are downgraded. In sum this may discourage taking action now. The same analysis without
216 discounting would allow for an average additional dyke increase of 4-11 cm along the European coastline over the
217 century (Table 6), which would imply additional mean annual coastal protection costs from 1.41 billion € to 2.21 billion
218 €, depending on the scenario. The benefits of such additional interventions would be that an additional 7.5% to 9.7%
219 of Europe's coastline would be protected to rising seas, and the EAD and EAPF by the end of the century would be
220 reduced by 5.1-16.4 billion € and 40 to 255 thousand people, respectively.

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223 Acknowledgments

224 PJW received additional funding from the Netherlands Organization for Scientific Research (NWO) in the form of a
225 VIDI grant (grant no. 016.161.324).

226 Author contributions

227 M.I.V. and L.F. jointly conceived the study. M.I.V. and L.M. produced the extreme sea level datasets. P.W, J.H.
228 produced the unit cost estimates for dyke height increase. I.M. and J.C.C. estimated the indirect losses from coastal
229 flooding. M.I.V. analyzed the data and prepared the manuscript, with all authors discussing results and implications
230 and commenting on the manuscript at all stages.

231 **Competing interests:** the Authors declare no Competing Financial or Non-Financial Interest

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358 Tables

359 Table 1. Expected Annual Damage (EAD, in billion €) from coastal flooding in 2100 under Sustainability, Fragmented World and
 360 Fossil Fuel Based Development, shown per country and for Europe.

	BASELINE	SUSTAINABILITY	FRAGMENTED WORLD	FOSSIL FUEL BASED DEVELOPMENT
BE	0.0	4.5	1.2	20.7
BG	0.0	0.1	0.3	0.6
CY	0.0	1.4	6.4	12.5
DE	0.1	6.0	4.9	38.8
DK	0.0	8.9	7.2	84.6
EE	0.0	0.1	0.1	0.6
ES	0.1	9.4	3.5	53.0
FI	0.0	0.3	0.5	6.2
FR	0.2	40.4	20.2	266.0
GR	0.1	4.9	4.8	20.8
HR	0.0	0.9	1.8	2.5
IE	0.1	14.5	6.5	89.1
IT	0.1	15.3	4.7	70.3
LT	0.0	0.2	0.6	0.4
LV	0.0	0.1	0.1	0.2
MA	0.0	0.0	0.0	0.0
NO		20.7	9.5	77.5
NL	0.0	25.6	19.0	200.1
PL	0.1	2.3	1.3	9.3
PT	0.1	2.2	0.6	8.7
RO	0.0	0.1	2.8	2.8
SE	0.0	4.2	3.1	46.2
SI	0.0	0.7	0.2	2.9
UK	0.4	47.2	21.7	254.3
EUROPE	1.4	209.8	121.0	1268.4

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365 Table 2. Expected Annual Number of People Flooded (EAPF, in thousand people) to coastal flooding in 2100 under Sustainability,
 366 Fragmented World and Fossil Fuel Based Development, shown per country and for Europe.

	BASELINE	SUSTAINABILITY	FRAGMENTED WORLD	FOSSIL FUEL BASED DEVELOPMENT
BE	0.5	13.1	11.5	31.7
BU	0.6	1.6	3.4	2.4
CY	3.0	13.8	22.7	17.2
DE	2.0	33.6	43.7	113.3
DK	1.0	79.2	94.7	273.4
EE	0.1	0.3	0.3	0.8
ES	8.1	182.4	131.1	346.1
FI	0.5	3.5	14.8	39.8
FR	3.5	145.9	159.8	393.2
GR	10.7	81.0	86.2	144.2
HR	9.2	31.3	86.8	41.6
IR	3.1	104.4	84.0	237.6
IT	12.7	200.9	143.3	382.3
LT	1.3	4.2	11.5	6.3
LV	0.2	0.4	1.3	0.8
MA	0.0	0.1	0.3	0.2
NL	0.6	5.4	5.2	12.9
NO		169.6	170.3	513.8
PL	9.9	24.2	18.8	46.9
PO	2.6	14.4	10.6	29.7
RO	0.5	2.3	6.4	3.4
SE	0.5	33.4	42.8	124.5
SL	2.4	6.2	3.5	10.0
UK	27.7	461.3	440.8	1126.1
EUROPE	100	1612.6	1593.9	3898.2

367
 368 Table 3. Percentage of the country's coastline with mean BCR>1 (benefits of adaptation exceed the costs) and mean country level
 369 benefit to cost ratio (BCR) over coastal stretches where additional protection is required. All data are shown for the three
 370 scenarios studied: Sustainability, Fragmented World and Fossil Fuel Based Development

	% COASTLINE BCR>1			MEAN COUNTRY LEVEL BCR		
	Sustainability	Fragmented World	Fossil Fuel Based Development	Sustainability	Fragmented World	Fossil Fuel Based Development
BE	85.0	85.0	95.0	16.6	8.9	25.8
BG	5.4	5.4	8.9	2.0	1.8	2.1
CY	22.9	28.4	27.5	11.1	13.0	15.6
DE	20.9	31.0	39.1	3.4	3.5	5.8
DK	22.8	29.6	48.3	3.0	3.8	6.9
EE	0.5	1.0	1.5	2.1	2.2	2.5
ES	46.9	40.9	56.2	8.1	5.8	15.1

FI	2.1	7.5	15.5	1.7	2.1	3.3
FR	58.3	56.7	66.3	10.5	8.7	24.8
GR	10.7	6.8	13.0	9.0	11.0	10.5
HR	8.3	10.9	10.4	1.9	2.4	2.3
IE	19.0	22.5	28.6	8.8	7.3	18.7
IT	52.6	44.1	59.1	9.7	5.6	16.4
LT	4.9	17.1	9.8	2.1	2.3	2.0
LV	3.2	3.2	3.2	2.1	2.5	1.8
MT	6.7	13.3	13.3	1.6	1.7	1.7
NL	40.1	38.1	40.8	21.1	18.9	34.3
NO	14.5	18.1	23.2	6.3	6.7	13.8
PL	24.6	24.6	30.7	3.9	3.6	4.5
PT	32.7	23.2	43.5	6.7	4.6	9.1
RO	3.3	13.1	14.8	2.4	2.2	2.2
SE	11.7	13.8	23.4	5.4	5.7	10.9
SI	50.0	50.0	50.0	3.7	3.3	5.9
UK	25.6	25.2	33.5	7.7	6.8	14.6
TOTAL	23.8	23.8	32.1	8.3	6.7	14.9

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372

373 Table 4. Annual mean costs of raising the dykes per country after discounting (million €), and corresponding mean, country-level
374 increase in dyke height (m), under Sustainability, Fragmented World and Fossil Fuel Based Development.

	COSTS (MILLION €)			PROTECTION HEIGHT INCREASE (M)		
	Sustainability	Fragmented World	Fossil Fuel Based Development	Sustainability	Fragmented World	Fossil Fuel Based Development
BE	0.16	0.59	0.48	3.43	2.23	2.85
BG	0.32	0.88	0.92	0.59	0.72	0.70
CY	0.77	1.33	1.50	0.80	0.96	0.97
DE	1.13	1.47	2.44	1.44	1.33	1.42
DK	1.65	4.77	2.52	0.88	0.97	1.00
EE	0.76	6.35	6.12	1.42	1.20	0.97
ES	8.68	7.03	9.33	0.61	0.68	0.82
FI	8.30	12.72	12.57	0.75	0.78	0.79
FR	8.86	14.98	14.37	0.93	0.99	1.12
GR	6.18	15.90	42.99	0.65	0.73	0.78
HR	26.22	19.40	37.03	0.50	0.65	0.64
IE	32.89	21.85	31.97	0.90	0.95	1.02
IT	37.72	40.05	49.67	0.72	0.79	0.92
LT	46.20	34.81	64.96	1.23	1.08	0.99
LV	27.37	41.39	91.55	0.83	1.41	1.35
MT	64.67	52.89	56.35	0.31	0.47	0.39
NL	75.48	98.40	135.29	1.53	1.32	1.30
NO	93.12	90.30	148.73	0.63	0.70	0.78

PL	90.20	128.83	224.06	1.57	1.67	1.66
PT	125.51	151.41	229.64	0.95	1.02	1.04
RO	180.28	167.66	260.92	0.62	0.96	0.87
SE	125.71	190.69	296.18	0.67	0.80	0.89
SI	269.72	287.85	385.01	2.12	1.72	2.32
UK	522.65	478.62	719.15	1.47	1.39	1.50
TOTAL	1754.55	1870.16	2823.76	0.92	0.95	1.04

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376

377 Table 5. Expected Annual Damage (EAD) and Expected Annual Number of People Flooded) from coastal flooding after
378 implementing additional protection (billion €), under Sustainability, Fragmented World and Fossil Fuel Based Development.

	EAD2100 ADAPT			EAPF2100 ADAPT		
	Sustainability	Fragmented World	Fossil Fuel Based Development	Sustainability	Fragmented World	Fossil Fuel Based Development
BE	0.03	0.07	0.03	13.10	4.29	29.21
BG	0.01	0.09	0.06	0.60	1.72	0.73
CY	0.05	0.36	0.21	8.06	12.51	8.63
DE	0.69	2.00	2.05	16.76	26.77	55.13
DK	1.14	2.47	2.82	26.42	47.76	54.45
EE	0.02	0.04	0.07	0.14	0.23	0.30
ES	0.35	0.92	0.96	73.78	72.46	100.99
FI	0.08	0.44	0.65	1.85	12.76	10.30
FR	0.89	2.27	2.40	55.88	49.77	140.92
GR	0.42	0.70	1.33	30.06	72.38	55.04
HR	0.13	0.58	0.39	10.72	36.40	14.59
IE	0.61	1.07	1.24	41.56	45.62	83.02
IT	0.68	1.62	1.95	44.69	74.50	69.31
LT	0.02	0.13	0.05	1.49	6.37	2.46
LV	0.01	0.04	0.02	0.15	0.73	0.31
MT	0.00	0.03	0.01	0.09	0.29	0.12
NL	0.23	0.49	0.87	4.94	4.82	7.90
NO	1.24	2.49	2.74	42.03	56.47	126.48
PL	0.07	0.23	0.32	12.43	10.81	18.20
PT	0.12	0.25	0.34	5.81	7.75	9.25
RO	0.02	0.76	0.65	0.85	2.91	1.24
SE	0.31	0.88	1.21	9.42	18.55	18.35
SI	0.01	0.01	0.02	0.25	0.62	0.38
UK	1.77	3.10	3.60	252.30	220.38	535.73
TOTAL	8.88	21.00	23.98	653.39	786.85	1343.05

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380

381 Table 6. Comparing results obtained with and without discounting for the entire European coastline, under Sustainability,
 382 Fragmented World and Fossil Fuel Based Development: reduction in Expected Annual Damage (EAD); Expected Annual Number
 383 of People Flooded) from coastal flooding after implementing additional protection (billion €); Annual mean costs of raising the
 384 dykes per country after discounting (million €); corresponding mean, country-level increase in dyke height (m); Percentage of the
 385 country's coastline with mean BCR>1 (benefits of adaptation exceed the costs); and mean country level benefit to cost ratio
 386 (BCR).

387

	SUSTAINABILITY	FRAGMENTED WORLD	FOSSIL FUEL BASED DEVELOPMENT
PROTECTION HEIGHT INCREASE (M)	0.04	0.10	0.11
EAD2100 ADAPT DECREASE	5.11	13.77	16.43
EAPF2100 ADAPT DECREASE	118.90	255.35	40.58
MEAN COUNTRY LEVEL BCR INCREASE	6.96	6.39	17.98
% COASTLINE BCR>1 INCREASE	7.53	9.73	7.76
COSTS (BILLION €) INCREASE	1.41	2.00	2.21

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391 Methods

392 Coastal flood risk and adaptation modelling framework

393 The coastal flood risk analysis is based on the model LISCOAST (Large-scale Integrated Sea-level and
394 COastal ASsessment Tool). The modular framework has been developed to assess weather-related
395 impacts in coastal areas in present and future climates. It combines state-of-the-art large-scale modelling
396 tools and datasets to quantify hazard, exposure and vulnerability and compute consequent risks². The
397 modelling framework was further extended to evaluate costs and benefits of heightening dyke heights
398 and find the optimal adaptation design based on maximizing the net present value. More details on the
399 different steps of the analysis are provide below.

400 Hazard assessment

401 Coastal flood impacts are driven by nearshore Extreme Sea Levels (ESLs). In this study ESLs are modelled
402 along the European coastline using segments of variable length with a maximum of 25 km for the most
403 straight coastline stretches. Our projections go to the end of the 21st century and we consider
404 Representative Concentration Pathways (RCPs) RCP4.5 and RCP8.5, for which an ensemble of 6 climate
405 models have been used to account for uncertainty in climate projections. RCP4.5 can be considered as a
406 moderate emissions-mitigation-policy scenario and RCP8.5 as a high-end, business-as-usual emissions
407 scenario. ESLs are calculated by adding linearly the contributions of different components:

$$408 \text{ ESL} = \text{SLR} + \eta_{\text{CE}} + \eta_{\text{tide}} \quad (1)$$

409 where

410 SLR is the Sea Level Rise, obtained from a GCM ensemble combined with contributions from ice-sheets
411 and ice-caps²⁹.

412 η_{CE} is the contribution from extreme wind and atmospheric pressure, driving waves and storm surge, that
413 is obtained dynamic ocean simulations^{29,30}.

414 η_{tide} the maximum tidal level sampled probabilistically to express the spring-neap variation of the high tide
415 water level.

416 We then apply in each coastal segment non-stationary extreme value analysis³¹ to the ESL projections.
417 From the fitted extreme value distributions we obtain ESLs for a range of return periods (inverse of
418 probability) between 2 and 20000 years. Hence, ESLs are expressed as a function of time and return
419 period¹

$$420 \text{ ESL} = f(\text{year}, \text{RP}) \quad (2)$$

421 The ESLs in equation (2) are subsequently used as forcing for coastal flood inundation calculations at 100
422 m resolution using the hydrological model Lisflood-FP³², taking into account present coastal protection
423 standards obtained from the FLOPROS dataset³³ and other available sources². Land surface elevation data
424 are provided from the Shuttle Radar Topography Mission (SRTM) DEM³⁴. This results in time-varying
425 coastal flood inundation maps for each of the considered return periods and for each coastal segment.

426 Exposure and vulnerability

427 The resulting flood inundation maps are combined with exposure and vulnerability information at the
428 corresponding point in time in order to estimate direct flood damages^{2,35,36}. Baseline exposure (reference
429 year 2012) is available from the refined CORINE land use/land cover dataset (CLC) at 100 m resolution,
430 featuring 44 different land use classes³⁷. Baseline population maps (reference year 2011) are available
431 from Batista e Silva et al³⁷. For future population exposure we used global projections gridded at 1/8°
432 resolution of population density and urban population³ based on the respective SSPs. The gridded
433 projections of urban population were considered as a proxy of the degree of urbanization. Given that
434 urban land use classes contribute to >90% of the estimated damages, relative changes in urbanization
435 were used to estimate changes in damages due to land use change. Consistent country level GDP
436 projections under SSP1, SSP3 and SSP5 are available from IIASA and OECD^{38,39}. The projected changes in
437 country-level GDP from both sources were spatially distributed according to the patterns of change in the
438 gridded projections of population. Asset values for future time slices were adjusted by scaling per NUTS3
439 region the depth damage functions according to changes in the future NUTS3 GDP per capita compared
440 to the baseline.

441 RCPs and SSP are combined according to van Vuuren and Carter²¹, who suggest that (i) RCP4.5 is
442 compatible with global sustainable development (Sustainability; SSP1); and (ii) RCP8.5 is compatible with
443 socio-economic development driven by mitigation challenges (SSP5), or both mitigation and adaptation
444 challenges (SSP3).

445 The vulnerability to coastal flooding of coastal infrastructure, societies and ecosystems is expressed
446 through depth-damage functions (DDFs)^{40,41}. DDFs define for each of the 44 land use classes of the refined
447 CORINE Land Cover the relation between flood inundation depth and direct damage. The country-specific
448 DDFs were further rescaled at NUTS3 level based on GDP per capita to account for differences in the
449 spatial distribution of wealth within countries.

450 Estimation of people flooded and direct losses

451 For each coastal segment, people flooded and direct flood losses in time for the different return periods
452 are calculated at 100 m resolution by combining the corresponding flood inundation maps with the
453 exposed people and assets and the vulnerability functions. Areas that are inundated on a regular basis
454 (which could happen in the future with sea level rise), here defined as the areas that lie below the high
455 tide water level, are considered as fully damaged and the maximum loss according to the DDFs is applied.
456 For areas inundated only during extreme events, the damage is estimated by applying the DDFs combined
457 with the simulated inundation depth for the respective return period events. For each coastal segment
458 this results in annual estimates up to 2100 of coastal flood damage D (and people flooded) for the range
459 of return periods considered

$$460 D = f(\text{year}, \text{RP}) \quad (3)$$

461 Probabilistic projections of flood impacts

462 Projections of future flood impacts are estimated in a probabilistic framework. For a correct statistical
463 description of the hazard, it is necessary to consider spatial dependency in the occurrence of extreme
464 events along the European coastline. If a severe storm hits a point along the coast, nearby locations will
465 likely also be exposed to extreme conditions, and neglecting such dependency would lead to an

466 underestimation of the aggregate risk. To that end, the spatial dependencies of ESLs were estimated
467 through copulas. Considering the spatial dependencies among coastal segments, we produce 10,000
468 realizations of sequences of ESLs during the present century through Monte Carlo simulations. This
469 produces annual time series of return periods (corresponding to the respective ESLs) for each coastal
470 segment. The time series cover 80 years from 2020 until 2100, resulting in a $80 \times 10,000$ matrix of extreme
471 event return periods (RP_{matrix}) for each segment, with dimensions corresponding to the number of years
472 and Monte Carlo realizations, respectively. The matrices of return periods are transformed into matrices
473 of direct losses (D_{matrix}) for each segment according to equation (3). The number of realizations was chosen
474 after several preliminary tests during which it was shown that 10,000 ensured convergence both in terms
475 of mean and standard deviation values (fluctuations below 0.001%).

476 Estimation of adaptation costs

477 In order to estimate the optimal dyke design for a coastal segment we consider dyke heights (Z_{prot}) that
478 vary from the current level ($Z_{\text{prot,pres}}$) to a maximum elevation. The latter exceeds by 1 m the 99th ESL
479 quantile estimated for that coastal segment during the present century (ESL_{max}). We discretize the range
480 between $Z_{\text{prot,pres}}$ and ESL_{max} in 40 increments. Hereby we assume that $Z_{\text{prot,pres}}$ is upgraded gradually to the
481 desired design between 2020 and 2050, and remains constant until the end of the century.

482 Costs of dyke heightening are calculated by aggregating investment and maintenance costs during the
483 entire study period. Investment costs are expressed as a linear function of dyke heightening; which has
484 been shown to be a good approximation⁴², and has been used in previous studies^{22,43,44}. Country estimates
485 of investment costs of dykes are available from two sources: (i) the dataset used in the analysis of global
486 investment costs for coastal defences of Nicholls, et al.⁴³; and (ii) the dataset used in the global flood
487 analysis of Ward et al.²². In both datasets costs are expressed as investment costs in US\$ per meter
488 heightening considering differences in construction costs across countries, which were converted to 2015
489 € values using GDP deflators and market exchange rates obtained from Eurostat. Maintenance costs are
490 assumed to be 1% per year of capital investment costs⁴⁵. The km length of dykes is equivalent to the
491 coastline length of each segment that was derived from OpenStreetMaps. Dyke heights are assumed to
492 be uniform over the entire segment. Both datasets on dyke unit costs come with confidence intervals, on
493 the basis of which cost probability density functions were fitted. In the probabilistic framework costs are
494 randomly sampled from these distributions assuming that each dataset has equal probability of
495 occurrence.

496 Estimation of adaptation benefits

497 Benefits are represented here as the avoided damages by increasing the dyke height in a coastal segment.
498 For each of the 40 increments, benefits are calculated for the 10,000 projections of ELS up to 2100
499 (equation 2) as the difference between future losses with and without additional coastal protection,
500 aggregated over the entire study period. We assume that if the ESL of the event (equation 2) does not
501 exceed the dyke height then the damage of that event will be zero. If the ESL overtops the dyke, then it
502 breaches and the damage is obtained from equation (3). For each coastal segment. This results in a matrix
503 of 40 increments vs 10,000 estimates of benefits.

504 Cost-benefit analysis

505 The objective of the cost-benefit analysis is to find the protection standard for each coastal segment that
506 maximises the Net Present Value (NPV). The latter is the sum over the project lifetime of the costs and

507 benefits associated with a specific investment and determines whether a project will deliver sufficient
508 benefits to justify the costs. We therefore sample 10,000 realizations of unit cost from the cost
509 distributions, which are used to generate 10,000 estimates of the (capital and maintenance) costs for each
510 of the 40 increments in a coastal segment. These are combined with the 10,000 realizations of benefits
511 for each increment, and the NPV is calculated. This results in 10,000 NPV values for each dyke increment.
512 This allows to derive the probability that a certain dyke design is cost-effective, and central estimates for
513 each increment can be used to choose an optimal dyke height. Here we use the mean NPV of the 10,000
514 NPV to choose the optimal design. For the dyke elevation that maximises mean NPV in a coastal segment,
515 we also calculate the Benefit-Cost Ratio (BCR), which is the ratio of its total benefits to its total costs.
516 Results at larger scales (e.g., NUTS2, country, or EU-level) are obtained by summing NPV estimates over
517 the coastal segments in the area of interest.

518 The benefits delivered by dykes often occur long after they have been constructed. Discounting is used to
519 reflect that the costs and benefits incurred in the future are of less value than those delivered in the near
520 term. In order to determine the present value of future costs and benefits, they are discounted and
521 aggregated according to

$$522 \quad X_{present} = \sum_{t=1}^T \frac{X_t}{(1 + r_{sw})^t}$$

523 where T represents the duration of the project's lifetime in years, X_t is the cost or benefit incurred over a
524 year by the project and r_{sw} is the social welfare discount rate. The choice of the latter can largely influence
525 the cost-benefit analysis of the adaptation measure. Larger values of r_{sw} tend to discourage the
526 implementation of the policy, as discounted future benefits of the measure become smaller compared to
527 its costs that are incurred earlier in time. We note that we limit T by putting 2100 as the end of the project
528 lifetime, yet in reality the lifetime of the dykes is likely longer.

529 We calculate the social discount rate using the Ramsey equation⁴⁶, which combines information about the
530 growth of the economy with two main parameters: the rate of pure time preference of society and the
531 elasticity of the marginal utility of consumption. The formula is:

$$532 \quad r_{sw} = \rho + \eta \cdot g$$

533 where:

534 ρ is the rate of pure time preference;

535 g is the growth rate of per capita consumption;

536 η is the elasticity of the marginal utility of consumption.

537 The Ramsey equation reflects the two main reasons why the society or a hypothetical social planner would
538 discount future benefits. A value of ρ larger than zero reflects impatience and a preference for
539 consumption in the current period rather than consumption in the future. On the contrary if ρ is equal to
540 zero, the society has no preference for a unit of consumption today or in the future. It is often referred to
541 as the inter-generational equity parameter, as it reflects preferences between the present and future
542 generations. The other reason why future costs and benefits are discounted is for the decreasing marginal
543 utility of consumption (η) and the growth rate of per capita income (g). A high value of η reflects a fast

544 declining utility as consumption increases. The interpretation is that the wealthier the society, the lower
545 the utility derived from an equal increase of the consumption level; therefore with a positive g , future
546 benefits will have a lower value in the present.

547 Here the Ramsey equation is calibrated using average growth rates for consumption per capita. As
548 suggested in the EC Guide to Cost-Benefit Analysis of Investment Projects⁴⁷, we distinguish between the
549 so-called cohesion countries, which benefit from the Cohesion Fund, and the rest of the EU Member
550 States⁴⁸. For the 2014-2020 period, the Cohesion Fund concerns Bulgaria, Croatia, Cyprus, the Czech
551 Republic, Estonia, Greece, Hungary, Latvia, Lithuania, Malta, Poland, Portugal, Romania, Slovakia and
552 Slovenia. From our macroeconomic projections the average growth rate of consumption per capita for
553 cohesion countries is equal to 2%, while for the rest of the countries is 1% per year.

554 We further assume a value of 1 for ρ , which is chosen as a central value between 0, i.e. no preference for
555 current or future generations, and 2, which is the value attributed by Weitzman in his review of the Stern
556 Review⁴⁹. Values of η in literature typically range between 1 and 4, with a central estimate of 2⁵⁰, which is
557 the value that we assume here.

558 With these values for g , ρ and η , the resulting discount rates are 5% for the cohesion countries (poorer
559 countries in Europe) and 3% for the other Member States. The resulting discount rates appear to be in
560 line with those suggested by the European Commission for the cost-benefit analysis of major investment
561 projects^{49,50}.

562 Data availability

563 The models and datasets presented are part of the integrated risk assessment tool LISCoAsT (Large scale
564 Integrated Sea-level and Coastal Assessment Tool) developed by the Joint Research Centre of the
565 European Commission. The dataset is available through the LISCoAsT repository of the JRC data collection
566 (<http://data.jrc.ec.europa.eu/collection/LISCOAST>).

567 Code availability

568 The code that supported the findings of this study is available from the corresponding author upon
569 reasonable request.

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