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ORIGINAL ARTICLE

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Greening the dike revetment with historic sod transplantation technique in a living lab

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Abstract

Coastal flood managers seek to anticipate future flood risk and as a result consider the adaptation of flood defences. Instead of crest heightening, dikes can be adapted to include hydrodynamic reducing vegetated foreshores to form a nature-based hybrid flood defence, for instance; at managed realignments. In this study we investigated the potential of vegetated revetments as a natural continuous connection between the realigned dike and restored foreshore. We applied the historic grass sod transplantation technique with the aim to improve our understanding of the strength of a transplanted sod revetment. In Living Lab Hedwige-Prosperpolder, dikes were available for in-situ experiments during managed realignment preparations. We transplanted grass sods and studied erosion resistance after one growth season. Our results show transplanted sod vegetation continued to grow and started to attach to the clay layer. While erosion occurred under extreme wave impact and overflow, the sod pulling method revealed individual sod strength. In conclusion, sod transplantation is a good technique to source local material for green realigned dike revetments. A vegetated dike revetment can hereby create a natural continuous connection between the realigned dike and foreshore, which benefits flood protection as well as flora and fauna.

KEYWORDS

hybrid flood defence, in-situ experiment, living lab Hedwige-Prosperpolder, managed realignment, nature-based flood protection, realigned dike, sod transplantation, vegetated dike revetment

1 | INTRODUCTION

Along many low-lying coasts and estuaries flood defences protect inhabitants against the risk of flooding. Flood risk infrastructure, such as dikes, has been built at places where natural features do not provide enough protection. Recently there has been an increasing focus on natural and nature-based features that provide nature-based flood protection (Bridges et al., 2022). For instance, on saltmarshes and mangroves that attenuate waves and reduce storm surges and high-water levels (e.g., Hochard et al., 2021; Mazda et al., 2006; Möller et al., 2014; Willemsen et al., 2020). Such nature-based 'green' flood protection is often combined with 'grey' flood risk infrastructure in hybrid flood defences (Schoonees et al., 2019; Sutton-Grier et al., 2015). Coastal flood managers seek to anticipate future flood risk and as a result consider the adaptation of flood defences. Flood defence adaptation can ensure future coastal safety and reduce possible flood damage costs (Hinkel et al., 2014; Vousdoukas et al., 2020). While nature-based flood protection is often self-adaptive, for example, saltmarshes can grow with sea level rise (Kirwan et al., 2016), current flood risk infrastructure is static. Static flood defences need to be maintained and, if required, adapted by humans to protect coastal populations that are increasingly exposed to subsidence and climate change induced sea level rise (IPCC, 2019; Nicholls et al., 2021).

In this study we focus on coastal dike adaptation. Dikes are also known as levees or flood defence embankments (CIRIA, 2013). Thousands of kilometres of coastal dikes must be adapted in the coming decades to ensure sufficient flood protection (e.g., Brown et al., 2021; Hinkel et al., 2014; Jorissen et al., 2016). Dikes need to be resilient to changing environmental conditions, including extreme hydrodynamic pressures from increasing water levels and waves and extreme weather (intense rainfall, drought), whilst also being sustainable in terms of duration and construction material. Dikes can be raised to combat increasing water levels. This however, is not only expensive and demanding (e.g., Mooyaart et al., 2023), but also impacts the (cultural) landscape. Increasing dike height often implies increasing dike width to ensure geotechnical stability (CIRIA, 2013). This requires space and due to increased dike weight can lead to subsidence of the dike and underlying sedimental layers (CIRIA, 2013). Furthermore, dikes create a static situation where sediment input to the hinterland is inhibited. Dikes also influence coastal ecology. In some situations dikes form migration passages (Beeftink, 1975) and thus create longitudinal connectivity for species. In other situations dikes form a barrier that can decrease the intertidal biodiversity (Beeftink, 1975) and cause coastal squeeze (Pontee, 2013). Often, the coastal dike revetment is partly 'grey' with a stone or asphalt cover protecting the dike toe (CIRIA, 2013). This grey revetment can form a barrier for flora and fauna (Schoonees et al., 2019).

The required flood defence adaptation provides an opportunity to simultaneously tackle ecological challenges such as biodiversity loss (IPCC, 2022). Instead of traditional dike crest heightening, dikes can also be adapted by integrating vegetated foreshores to form a hybrid flood defence (Bridges et al., 2021). A foreshore is the sediment body fronting a dike on the waterside, for example a tidal flat or saltmarsh. Vegetated foreshores reduce hydrodynamic forcing on the adjacent dike and lessen the need to adjust dike crest height and revetment (van Loon-Steensma & Kok, 2016; van Wesenbeeck et al., 2022; van Zelst et al., 2021; Vuik et al., 2016). Even if the dike of a hybrid flood defence breaches, the foreshore mitigates flooding impact in the hinterland (van den Hoven et al., 2023; Zhu et al., 2020). At coastlines where vegetated foreshores disappeared due to land reclamation, managed realignment can be applied to restore foreshores (Esteves, 2014a; Temmerman et al., 2013). Managed realignment is the landward relocation of flood defences to restore nature on formerly reclaimed land (Esteves, 2014b; French, 2006). At managed realignment sites hybrid flood protection is provided by the flood risk reduction capacity of the restored foreshores complemented by the landward relocated flood defence (Bridges et al., 2021), that is, the (reinforced) existing or newly constructed realigned dike (van den Hoven et al., 2022). While managed realignment facilitates flood protection and nature restoration, we note managed realignment can result in trade-offs from a social perspective (Bax et al., 2023; Schuerch et al., 2022).

Even though the realigned dike and foreshore can be combined for hybrid flood protection, realigned dikes are not automatically prepared for a connection with the restored foreshores (van den Hoven et al., 2022). In a hybrid flood defence, a continuous connection between the dike and vegetated foreshore is important for two reasons. First, it reduces the flood risk at revetment transitions (Simm et al., 2021; van Bergeijk et al., 2022). Second, it reduces the ecological barrier by creating an ecological connection between the aquatic and terrestrial habitats. We expect that a green, vegetated, revetment prepares the realigned dike for a sound continuous connection with the restored foreshores. The foreshores reduce hydraulic impact on the dike, so the (realigned) dike can have a vegetated revetment (Waterloopkundig Laboratorium, 1984). Furthermore, with a vegetated revetment; vegetation of the restored foreshores can expand onto the (realigned) dike. This way, the vegetated foreshore and dike can be combined in a continuous hybrid flood defence (Schoonees et al., 2019; Sutton-Grier et al., 2015).

Traditionally, a vegetated revetment is created by sowing the dike. However, after sowing it takes up to 5 years before the new revetment is erosion resistant (Muijs, 1999). A faster option to create an erosion resistant vegetated revetment might be the historic sod transplantation technique (Bartels, 2017; Bazelmans et al., 1999). In history, sods from saltmarshes and hinterland have been frequently used in northwestern Europe to construct or reinforce dikes and as emergency dike repair material (Bartels, 2017; Bazelmans et al., 1999; Gerritsen, 2016; Muijs & Sprangers, 1997). Coherent pieces with vegetation and sediment were cut out and these sods were transplanted to the dike. Sods of mainly clay formed the dike core and vegetated sods were transplanted to seal the dike with a vegetated cover (Bartels, 2017; Bazelmans et al., 1999). Nowadays, vegetated sods can be locally sourced and transplanted onto the realigned dike. Existing foreshores and the old dike can hereby form a vegetation source for the new realigned dike revetment. With this, there are not only practical and economical but also ecological benefits. Local, autochthonous mined sediment is preferred in regard to ecology and local acquired sods deliver area specific (ecologically adapted) flora and fauna species.

In this study we test locally sourced materials as a faster way to create an erosion resistant, vegetated, realigned dike revetment. We apply the historic sod transplantation technique. Our aim is to improve our understanding of the strength of a transplanted dike grass sod revetment in a Living Lab. Implementation of innovative flood protection solutions such as reintroducing the historic sod technique is often hampered by the lack of opportunities to study in-situ flood protection performance under extreme conditions (e.g., van Loon-Steensma et al., 2012; Vuik et al., 2018). Fortunately, the Living Lab Hedwige-Prosperpolder provided a unique opportunity to test innovative methods on real dikes under simulated extreme conditions. Insights obtained at this specific site are also valuable for managed realignments in other countries and for flood managers of different dikes.

2 | METHODS

2.1 | Study area

To test the historic sod technique for dike revetments an in-situ experiment was set up in a Living Lab. Coordinated by the INTERREG Polder2C's project, the Living Lab Hedwige-Prosperpolder was available for research during managed realignment preparation (further reading in van den Hoven et al., 2021). This preparation provided the unique opportunity to research dikes in-situ. The former primary dikes were available for research from summer 2020 until spring 2022.

The Living Lab Hedwige-Prosperpolder was located along the brackish part of the Scheldt Estuary, on the border of The Netherlands (Hedwigepolder) and Belgium (Prosperpolder) (Figure 1). Here, the average tidal range is 5.0 m, average high water level +2.77 m NAP (mean sea level) and average low water level −2.24 m NAP (www.waterinfo.be). Wave climate is mild and waves mainly originate from ships sailing to and from the port of Antwerp.

Our field experiment was conducted at two locations on the former Dutch sea dike along the Scheldt Estuary (Figure 1). In general, this dike had a sand core with vegetated clay top layer varying between 0.5 and 1.0 m. The first location was the waterside slope (Figure 1). This outer slope was 1:4, had an intermediate berm, grass cover except for stone armour at the lowest few metres, and was fronted by Common Reed (*Phragmites australis*) foreshores (elevation up to +3.0 m NAP). The second location was the landside slope 400 m southeast from the waterside location (Figure 1), near other dike revetment treatment experiments (Koelewijn et al., 2022). This inner slope was 1:3 and had a 0.6 m clay top layer and grass cover. The vegetated revetment was characterised as species poor *Arrhenatherum* (False Oat grass) grassland (Vandevoorde & van Lierop, 2021).

2.2 | Field experiment set-up for sods transplantation

The main experiment was set up at the bottom part of the waterside slope (Figure 1). Six plots measuring 8 m by 4 m plots were created (Figure 2): three plots were untreated and served as a reference (R1, R2, R3) and three were treated with transplanted sods (S1, S2, S3). One additional plot measuring 4.1 m by 10.9 m on the landside slope (plot S4) was surplus to the main set-up to allow for an overflow test (Figure 2). Landside reference measurements were taken in plot R4, next to plot S4 (Figure 2). Plots S1-S4 were treated with transplanted sods that were locally sourced from the to-be realigned dike landside slope (Location 0, Figure 1). The to-be realigned dike also had a plant species-poor *Arrhenatherum* grassland revetment (Vandevoorde & van Lierop, 2021). Reference plots (R1-R4) were untreated and represented a well-developed plant species-poor *Arrhenatherum* grass cover.

The sod transplantation technique consisted of several procedures. First, plots S1-S4 were prepared by

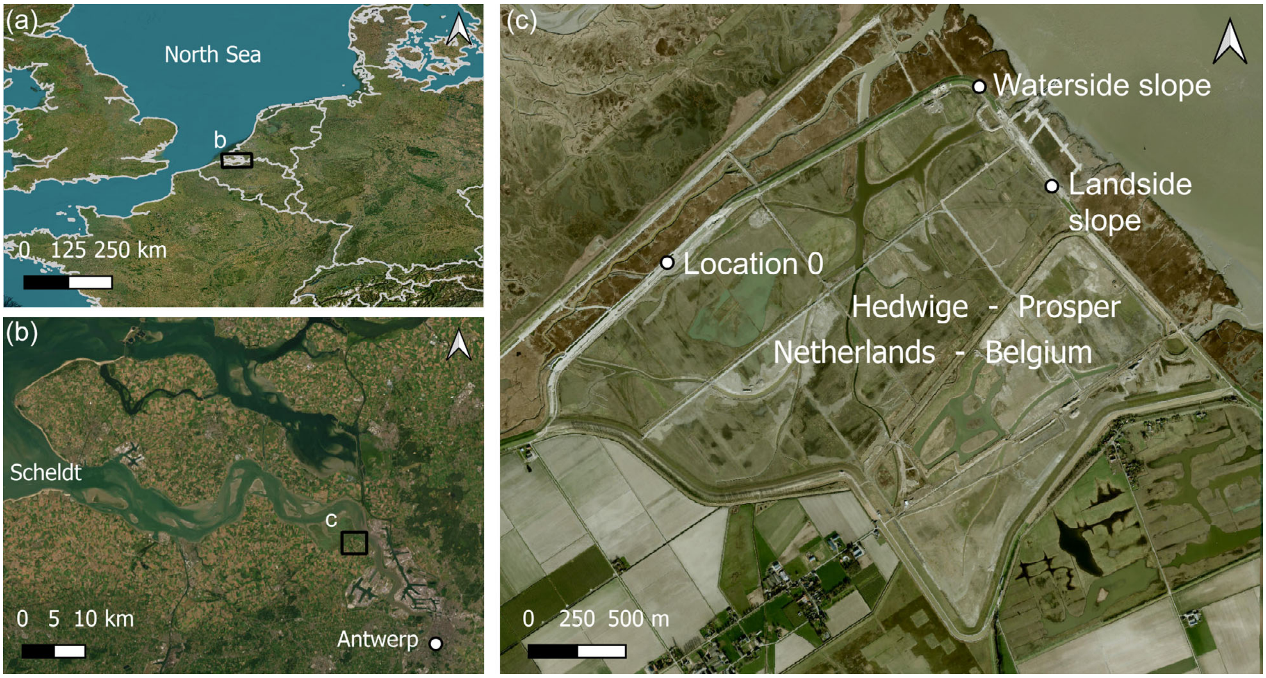


FIGURE 1 Location of the study in the Living Lab Hedwige-Prosperpolder. The in-situ experiment was conducted on the waterside and landside dike slope (c), before this dike was removed as part of a managed realignment (October 2022). Background images: ESRI Satellite images.

milling the original vegetation layer. This allowed for sod connection with the dike. The damaged vegetation was left in place serving as fertilizer. Individual 1.4 m by 2.0 m sods were then taken from the to-be realigned dike (Location 0, Figure 3a) and transplanted to the prepared plots on the waterside (S1, S2, S3 on 23 February 2021) and landside (S4 additionally on 21 April 2021) (Figure 3, Video 1 in van den Hoven, 2023). Between each plot a few metres were kept free to minimize interference (exact values in Figure 2). Sod thickness varied between 0.13 and 0.15 m. Sods were placed next to each other (Figure 3c) and pressed (Figure 3d) to enhance firm connection with the dike. Joints between the individual sods were sealed with clay (mainly at the waterside slope). The weather condition at the end of February 2021 was relatively sunny and dry, so the waterside plots were watered three times.

2.3 | Data collection

The flood protection value of a dike grass cover is mainly related to erosion resistance. Based on common practice for grass cover inspection by Dutch dike managers (RWS, 2022; Steendam, 2017) we distinguished five main steps in the data collection (Table 1). The five steps are: visual observation, abiotic soil factors monitoring, root indication, sod pulling method, and large scale tests under extreme circumstances (wave impact and overflow). As erosion resistance is most relevant during storm season (1 October– 1 April) when high water levels and wave impact chances are highest, most measurements were done in winter vegetation state.

In the first step (Table 1) we visually observed the revetment based on the Dutch dike assessment method 'WBI' (RWS, 2022). We noted: overall revetment coverage (vegetation vs. bare soil), vegetation type (general species), vegetation length (manual measurements), and revetment relief. In addition, we cut out a 0.25 m by 0.30 m sod (thickness 0.05–0.20 m) and noted approximate root density, root presence, sod tear strength, and sod intactness.

In the second step (Table 1) two abiotic factors; soil moisture content and soil penetration resistance, were measured perpendicular to the dike slope to study the clay underneath the visible vegetation. Soil moisture content was measured at 0.06 m depth using a ML3 ThetaProbe (Delta-T Devices) (Figure 2, Table 1). Soil penetration resistance was measured up to 0.8 m deep, using a penetrologger (Royal Eijkelkamp) with cone type 1.0 cm^2 and penetration speed 2 cm/s. Each sampling location consisted of four penetrations 0.50–0.60 m apart (Figure 2).

In the third step (Table 1) we visually estimated root density as an indication of erosion resistance. Instead of direct root counting, which is time consuming, we

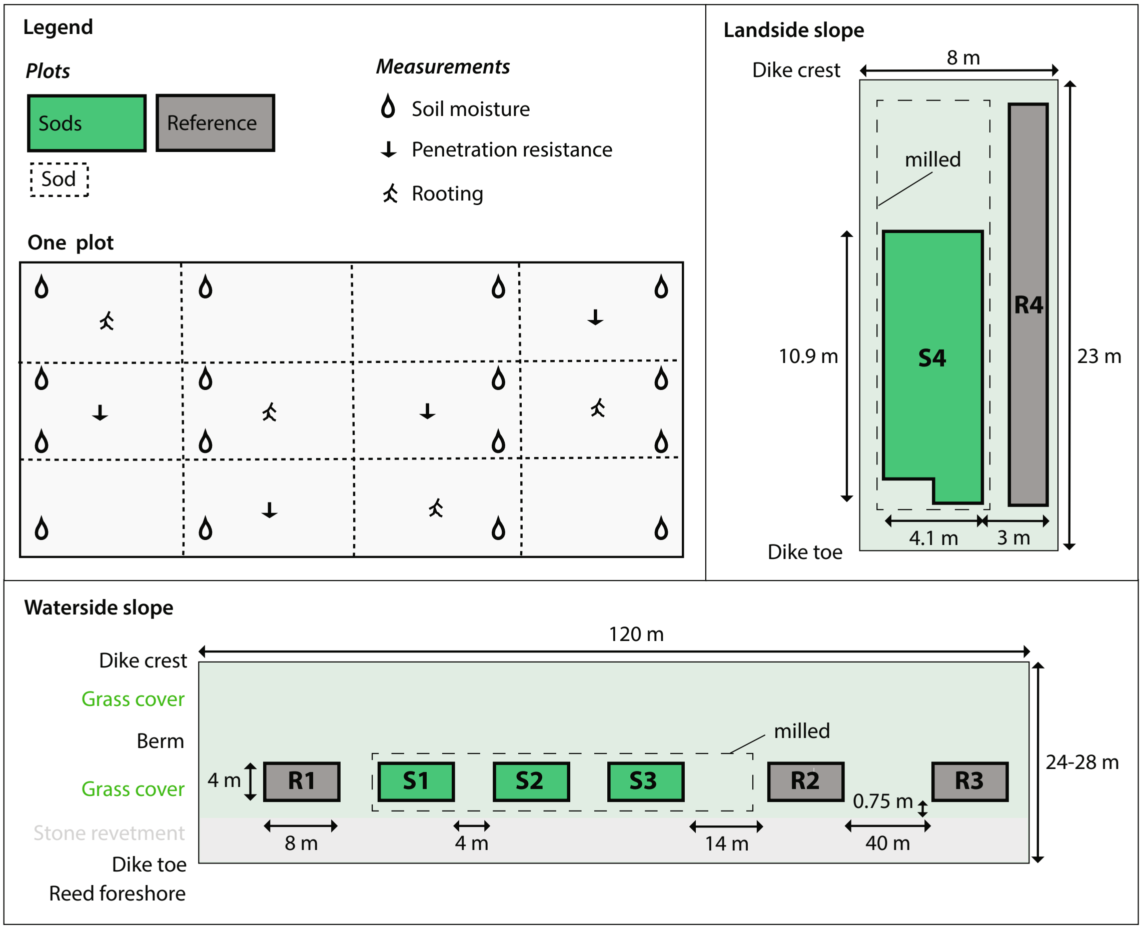


FIGURE 2 Sod transplantation experiment set-up. With plots on waterside and landside dike slope, including the measurements within one plot. At the waterside, the space between two plots is 4 m unless noted otherwise. Figure is not to scale.

applied a root estimation method 'VTV' (Voorschrift toetsen op Veiligheid) commonly used by dike investigators (MVW, 2007; Sprangers & Arp, 1999). The VTV method is described in detail and visualized in Figure S1. In short, we took 0.20 m soil samples with a gouge auger (diameter 0.03 m). Each sample was divided into eight 0.025 m sections for which we estimated root density into categories (Table 2, Figure S1). Although this method only includes roots with a minimum length of 0.01 m, we did note if many tiny roots were present.

Steps four and five were destructive to the dike revetment, so these were each only applied in one plot per group. In the fourth step (Table 1), erosion resistance was indirectly measured with the sod pulling method by INFRAM Hydren (as described in Bijlard et al., 2017). The sod pulling device pulled out 0.2 m by 0.2 m revetment pieces to determine the maximum pull force [N] (Video 2 in van den Hoven, 2023). Fifteen samples were taken in each plot. All samples were evenly spread without interfering with each other and they were all inside an individual sod.

In the fifth step (Table 1), extreme situations were simulated using a wave impact generator and an overflow generator (Figure S2, Video 3 and Video 4 in van den Hoven, 2023). The wave impact generator (Figure S2a, van Steeg et al., 2014) can generate wave impacts corresponding to an estimated significant wave height of 0.7 m and wave steepness of 4%–5%. Hereby generating approximately the largest one-third of impacts (viz those most relevant for erosion) except for the highest 2% (van Steeg et al., 2014). Waves were reproduced at three locations along the slope: in the middle (0), at +0.4 m, and at −0.4 m. During each cycle 20 waves were released per location. In total 720 waves were reproduced during 12 cycles, simulating a storm duration of 1.5 h. Erosion values were measured in a grid with a fixed frame after cycle 1, 2, 3, 6, 8, 12 (plot S1) and 1, 4, 8, 12 (plot R1) (Daamen et al., 2022).

The overflow generator (Figure S2b, Vercruysse et al., 2023) can generate a flow up to 1.1 m^3/s at the dike crest. To test the sod revetment, up to 200 L/s/m was supplied over the middle two meters of plot S4 during eight

FIGURE 3 Grass sod transplantation technique. Grass sods excavated at Location 0 (a) and transplanted to experimental plots at the waterside dike slope (plot S1 in b, c, d and S2 in e, f). Sods were placed on the milled dike revetment (b, c) and pressed (d) to enhance firm connection with the dike. (e, f) Impression of sods plots after transplantation. Locations in Figure 1.

consecutive test runs (Table S2). Flow was applied for 2 h in total (Table S1). Discharge and flow duration increased over time (Table S1). Water levels were measured by three sensors along the dike slope: at the crest, upper slope, and lower slope (Figure S3). The dike revetment part above plot S4 was protected with a geotextile in run 1–6 and only received water in run 7–8. Erosion values were only obtained afterwards. Erosion depth was measured from the top of the remaining applied sods with a soil erosion measurement device.

2.4 | Data analysis

For each research step, we compared the reference group (R1-R4) with the transplanted sods group (S1-S4) to improve our understanding of the strength of dike revetments with transplanted dike grass sods after one growth season. We note sample sizes differ between the two locations due to the different set-up (main experiment at waterside slope and additional plot at landside slope). Normality was assessed by creating QQ plots in

TABLE 1 Overview data collection per research step. When column shows the date (DD-MM-YY).

Step	What	Device	Which plot	Sample size per plot	How often	When
1.	Visual observation	-	All	1	1	Before step 5
		WBI (RWS, 2022)	R1 R2 R3 S1 S2 S3	1	1	24,27-01-22
2.	Soil moisture content	Thetaprobe	R1 R2 R3 S1 S2 S3	16	3	19-03&16-04-21 & 18, 24-01-22[a]
			R4 S4	6, 11, 9[c] 9, 28, 30[c]	3	04 & 23 & 29-11-21
	Soil penetration resistance	Penetrologger	R1 R2 R3 S1 S2 S3	4	1	18,24-01-22[a]
			R4 S4	9 28	2	23-24 & 29-11-21
3.	Root indication	Gouge auger	R1 R2 R3 S1 S2 S3	4	1	10-02-22
			R4 S4	5 10	1	12,17-11-21
4.	Sod pulling method	Sod pulling device[e]	R2 S2	15	1	23,24,25-02-22
5.	Wave impact test	Wave impact generator[ef]	R1[b] S1	1	1	27-01-22[d] 26-01-22
	Overflow test	Overflow generator[fg]	S4	1	1	24-11-21

[a]Divided over 2 days: R1 and S1 on 18 January 2022 before the wave impact test and remainder of plots on 24 January 2022.
[b]Partly outside plot R1 for logistic reasons.
[c]Order of sample size corresponds with different dates. Sample size differed due to different coverage of the plots.
[d]And the final run on 28 January 2022.
[e]By INFRAM Hydren.
[f]Facilitated by Interreg 2Seas project Polder2C's.
[g]Vercruysse et al., 2023, and referenced as plot N-OF08 'Grass sods' in Koelewijn et al. (2022).

TABLE 2 Estimated root density and corresponding root categories (MVW, 2007).

Root density	Root category
40+	5
21–40	4
11–20	3
6–10	2
1–5	1
0	0

MATLAB. Then all further statistical analyses were performed in Microsoft Excel. Results were considered significant at $p < 0.05$.

The visual observations (step 1) were qualitatively categorized according to the Dutch dike assessment method WBI (RWS, 2022). Vegetation quality was categorized as closed, open, or fragmented. The soil moisture content (step 2) was analysed at each location (waterside and landside). For each location, the two groups were compared statistically by single-factor ANOVA and averages were calculated for individual plots. Due to the weather and seasonal influence, soil moisture values were only intercomparable on each measurement day. The soil penetration resistance (step 2) was compared for each plot. For each sampling location (4/plot), the four penetrations were averaged to get one representative resistance value in megapascal (Mpa) along a depth profile (0 to −0.6 m).

The rooting estimation (step 3) resulted in categorical data instead of exact values. We qualitatively compared the root categories per 0.025 m depth for each plot. In addition, we combined all waterside depth values to get 96 samples per group (8 depths × 4 sample size per group

× 3 plots per group). This way, we could statistically compare the waterside sod and reference group with a Chi-square test of homogeneity (assumptions: no expected cell count <1 and ≥20% of expected values <5). To obey the assumptions, we left out category 0 (no roots) as all samples contained at least one root.

The sod pulling method resulted in measured pull forces [N] per sample (step 4). For each sample, the maximum pull force [N] was converted into the critical normal strength [N/m^2] (Bijlard, 2015). This strength was averaged per plot and compared by single-factor ANOVA. The representative grass cover strength is related to the weakest point at which failure might occur. In The Netherlands, it is common practise to represent this by the 2.5% undershoot value (Bijlard, 2015). The 2.5% undershoot value of the critical normal strength ($\sigma_{grass,c(2.5)}$) was therefore determined using the plot's average, standard deviation, and critical *t*-value (2.14 for df = 14 and probability = 2.5%). Finally, critical flow velocity (U_c [m/s]) was estimated with Equation (1) (Bijlard, 2015). For Dutch clay dikes with a grass cover, the U_c is 6.6 m/s for a closed revetment and 4.3 m/s for an open revetment (RWS, 2022).

$$U_c = \frac{0.34}{0.12}\sqrt{\frac{\sigma_{grass,c(2.5)}}{1000}} \qquad (1)$$

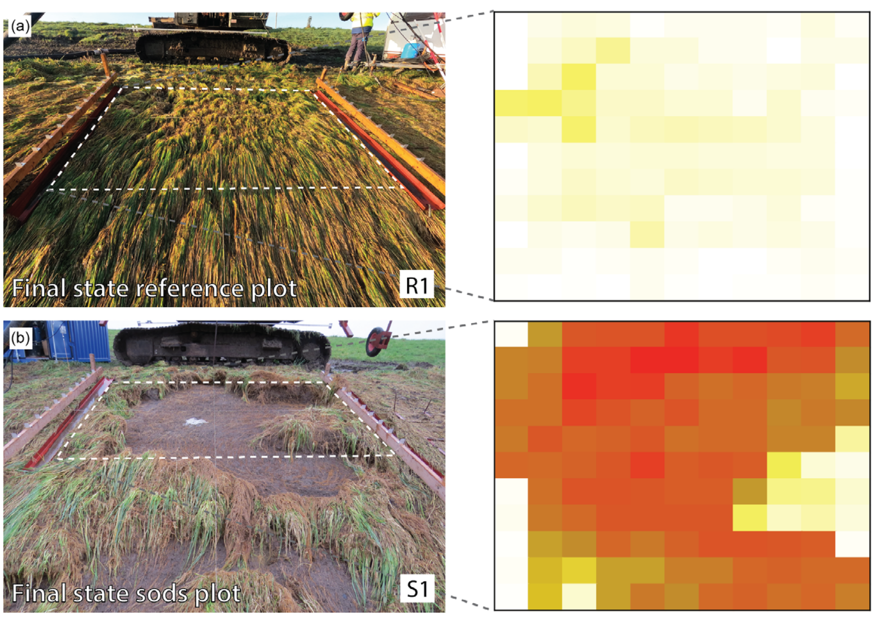
The overflow and wave impact (step 5) observations after each run were first compared qualitatively. Next, for the wave impact test, erosion values [m] were calculated for each run by subtracting measured from initial values to indicate erosion pattern over time.

3 | RESULTS

3.1 | Extreme events impact

After one growth season we measured erosion during simulated wave impact and overflow to determine the strength of a transplanted sod dike revetment under extreme circumstances. While the transplanted sods started to attach to the original dike clay layer, the wave impact and overflow simulation still eroded parts of the transplanted sods (Figures 4 and 5). We note milling impact was clearly visible at the landside dike slope (tracks in Figure 5b). Nevertheless, the original dike clay beneath the sod and milled layer seemed largely undamaged.

The transplanted sod revetment was eroded in a similar pattern during the extreme impact of waves (plot S1, Figure 4) and overflow (plot S4, Figure 5). Water flow converged between the individual (1.4 × 2 m^2) sods and erosion started at the joints between the sods. Step by step, sod pieces were eroded (Figure 4c and visualization in File S1 and File S2). The flow convergence was most apparent during the overflow simulation. Here, a channel was quickly formed in the middle between two sod columns (Figure 5a and File S2). From this channel the transplanted sods were undercut. Eventually parts of



(c)

Runs	Wave impact (#)	Maximum erosion depth (cm)			
		Q 1	Q 2	Q 3	Q 4
Reference R1					
1	60	-3.5	-1.5	-2.5	-1.5
4	240	-6.0	-3.5	-3.0	-2.5
8	480	-10.5	-4.5	-4.5	-7.5
12	720	-17.0	-5.5	-7.0	-4.0
Sods S1					
1	60	-17.5	-4.5	-8.5	-15.0
2	120	-23.5	-4.5	-14.5	-16.0
3	180	-27.5	-5.0	-25.0	-19.5
6	360	-28.5	-16.5	-26.0	-24.5
8	480	-29.5	-22.5	-27.0	-27.0
12	720	-30.5	-30.0	-28.5	-27.0

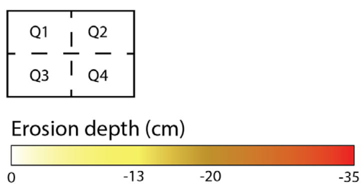


FIGURE 4 Wave impact effect on waterside slope. (a, b) Final state of the revetments with erosion depth within the measurement frame. (c) Maximum erosion (cm) per quadrant (Q1, Q2, Q3, Q4) of the measurement frame. Data collected for this research by INFRAM Hydren (Daamen et al., 2022). Photograph R1 by INFRAM Hydren.

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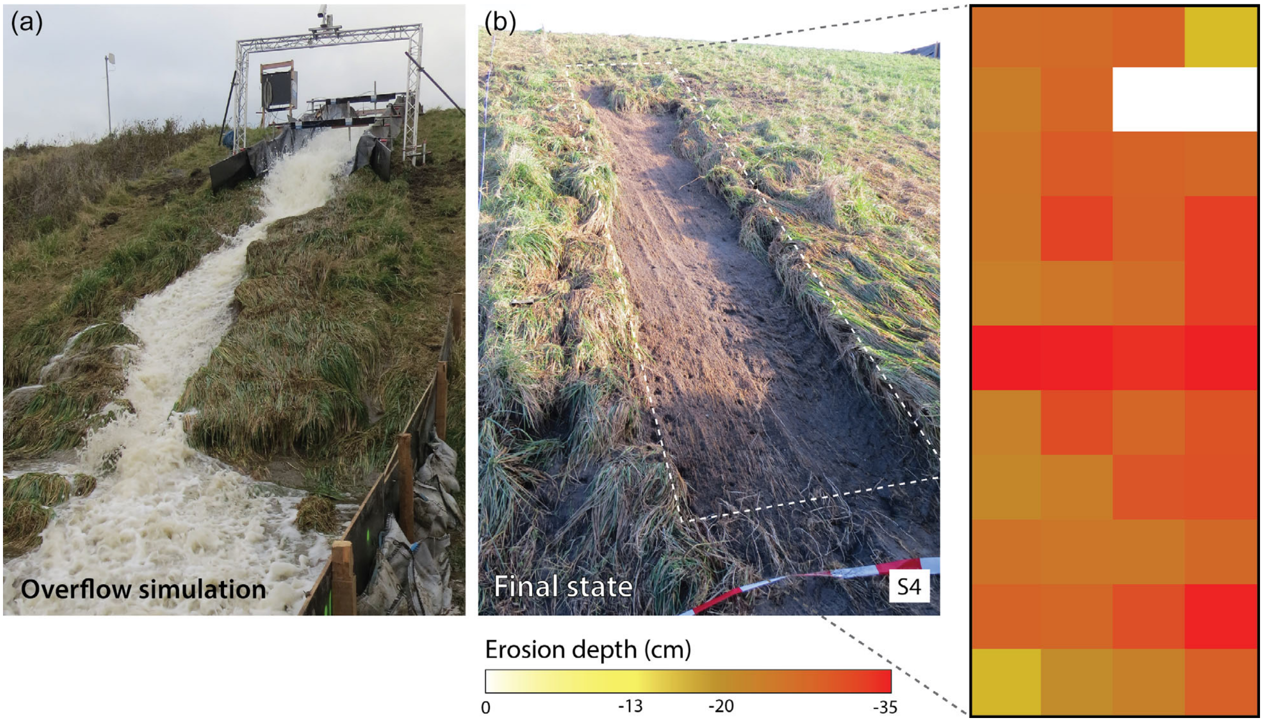

FIGURE 5 Overflow effect on landside slope. (a) Overflow during run 4. (b) Final state of the revetment after overflow with erosion indication.

the upper vegetated layer (including roots) remained overhanging at both flow channel sides (File S2). This overhanging vegetation layer was also formed during the wave impact test (File S1). Erosion built up over time and the first wave impact cycle did not immediately erode the sod layer (Figure 4c). The same accounts for the overflow test (File S2). In the final state, maximum erosion depth was 0.305 m (wave impact, Figure 4c, Figure S4) and 0.337 m (overflow, Figure S5). These depths include the 0.13–0.15 m sods and few centimetres milled clay.

3.2 | The dike revetment with transplanted grass sods in more detail

The strength of dike revetments with transplanted dike grass sod was also determined under calm conditions by the sod pulling method and root density estimations. After one growth season, the transplanted sod revetment was weaker than the well-developed reference revetment (Figure 6). The sod pulling method determined an average critical normal stress of 1.581 N/cm^2 (std 0.457) for reference plot R2 and 1.050 N/cm^2 (std 0.345) for sod plot S2 (Figure 6a). The strength was significantly lower for the sod revetment when compared to the reference revetment ($p = 0.0012$, Figure 6a). Related estimated critical flow velocities were 9.8 m/s (R2) and 6.9 m/s (S2).

Root density estimations were low in most transplanted sods samples (Figure 6b). All sod plots had averages below root category 3, already from the top 0.025 m (Figure 6). Rooting was significantly higher in the refence plots ($p = 3.007\text{E-}10$ for the waterside slope). In the transplanted sod samples we mainly observed tiny roots, which lead to the low root categories (Section 2.3). Based on the root estimations the reference plots are classified as moderately rooted and the sod plots as very poorly rooted (Figure S6).

Furthermore, abiotic soil factors in the top layer differed between the reference and sod revetment. Penetration resistance only differed in the top 0.35 m (Figure 7a). The top 0.13 m containing the transplanted sods all had a lower resistance than the reference top 0.13 m (Figure 7a). Underneath the sods, the increase in resistance was more comparable to the reference plots. From 0.35 m depth, penetration resistance was similar for the reference and sod plots. In general, the transplanted sod plots had a lower soil moisture content than the untreated reference plots. On each measurement day, the reference group differed significantly from the sods group ($p < 0.05$) at both the waterside (Figure 7b) and landside slope (Figure 7c). At the waterside slope, $p = 4.69\text{E-}5$ on 19 March 2021, $p = 8.51\text{E-}10$ on 16 April 2021, $p = 6.99\text{E-}18$ in January 2022. At the landside slope, $p = 5.12\text{E-}4$ on 4 November, $p = 0.023$ on 23 November, $p = 0.038$ on 29 November 2022.

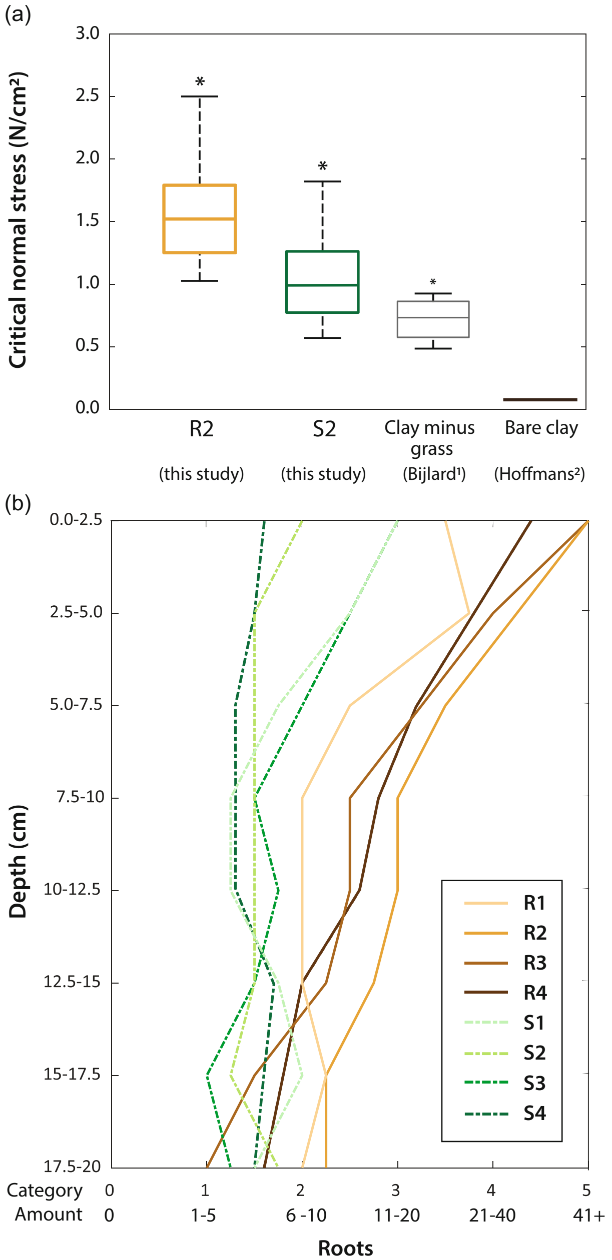

FIGURE 6 Dike revetment strength. (a) Determined by sod pulling method. * $p < 0.05$. [1]Four tests where top 0.20 m vegetated layer was removed (with some root structures remaining). [2]Value for good quality dike clay. (b) Estimation of root density for each 0.025 m of depth, average values for each plot.

In addition, visual observations revealed tall vegetation and revetment openness of the sods plot in comparison to the reference plots (Table S2). One month after sod transplantation, vegetation cover was denser at the reference than at the sod plots (Table 3, Table S2). Based on the Dutch WBI judgement, the reference revetment was classified as either 'open' or 'closed' and all sod revetments as 'open' (Table 3).

4 | DISCUSSION

4.1 | Strength of transplanted dike grass sod revetment

In this unique Living Lab study we investigated vegetated dike revetments to prepare realigned dikes for a continuous connection with vegetated foreshores. Historically, in northwestern Europe vegetated sods were transplanted from nearby saltmarshes or land and have been used to cover newly built dikes (Bartels, 2017; Bazelmans et al., 1999; Muijs & Sprangers, 1997). We tested this historic sod transplantation technique for modern dikes in Living Lab Hedwige-Prosperpolder. The aim of this study was to improve our understanding of the strength of a transplanted dike grass sod revetment. Overall, in our in-situ experiment transplanted sods vegetation continued to grow, and sods started to attach to the dike. Even though after one growth season the erosion resistance was not yet at the level of a well-developed dike revetment, grass sods transplantation is a promising technique for a greener realigned dike.

The sod pulling method revealed the tensile strength of individual (1.4 m by 2 m) sods. Based on sod pulling, the estimated critical flow velocity (6.9 m/s) is above the Dutch standards minimum of 4.3 m/s for an open and 6.6 m/s for a closed vegetated revetment on clay dikes (RWS, 2022). Despite our relatively small sample size ($n = 15$) this indicates that after 1 year the individual transplanted sods can offer the required resistance to withstand expected shear forces. Even though estimated root density was low in reference and sods plots (Figure 6b), the many tiny roots might have added to the transplanted sod revetment strength. The grass sods pull strength was clearly larger than of a (bare) clay cover (Figure 6a, Bijlard et al., 2017; Hoffmans, 2012). Other sod pulling tests within the same Living Lab revealed estimated critical flow velocities at untreated grass covers of 6.5 m/s (Dutch dike) and 5.0 m/s (Belgian dike) (Daamen et al., 2023). In similar tests at dikes along the Dutch Wadden Sea critical flow velocity of existing grazed dikes varied from 7.77 to 10.65 m/s (Schippers et al., 2018). This Wadden Sea dikes study is comparable to our reference plot, while the other Living Lab tests values are comparable to our transplanted sods plot.

The overflow and wave impact tests showed one growth season is too short to firmly attach transplanted sods to each other and to the dike clay layer. Under extreme circumstances parts of the transplanted sod revetment eroded over time (Figures 4 and 5). Other dike reinforcement test sections in the same Living Lab were also unable to resist overflow for more than a couple of

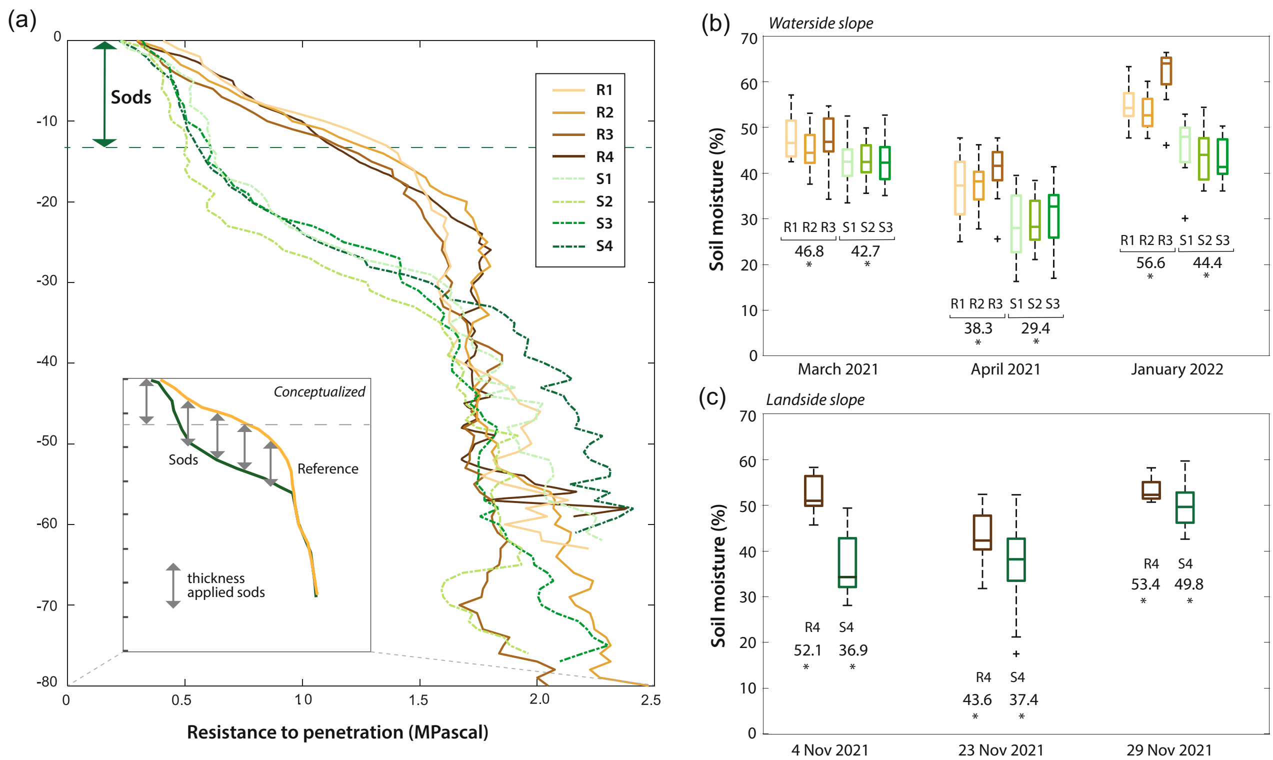

FIGURE 7 Soil measurements. (a) Soil penetration resistance (MPascal) up to 0.8 m deep, with a theoretical conceptualization based on the averages. (b, c) Soil moisture content (%) at a depth of 0.06 m. Sample size differs for each day and plot at the landside slope (c). *$p < 0.05$. Depth is perpendicular to the dike slope. Some penetrologger measurements were aborted due to the presence of hard substrate.

TABLE 3 Visual revetment judgement, based on the Dutch WBI (RWS, 2022).

Plot	R1	R2	R3	S1	S2	S3
Vegetation view	Open	Closed	Open	Frag/Open	Open	Open
Plant distance	Closed	Closed	Open	Open	Open	Open
Revetment relief	Closed	Closed	Closed	Open/Frag	Frag[a]	Frag[a]
Sod strength & intactness	Closed	Closed	Closed	Clos/Open	Closed	Open
Root presence	Closed	Closed	Closed	Closed	Closed	Closed
Rooting density	Closed	Closed	Closed	Closed	Closed	Open
Final	Open	Closed	Open	Open	Open	Open

Note: Three values per category: closed, open, fragmented (Frag).
[a]Due to unevenness in grass sods.

hours (Depreiter et al., in prep; Koelewijn et al., 2022). However, complete individual 1.4 by 2 m sods did not erode all at once. So, if the vegetated sods would have had more time to root and attach to the clay layer, the erosion resistance might have increased to a comparable strength of the reference dike revetment. Similar overflow tests in the same Living Lab revealed well-developed vegetated revetments without anomalies can resist overflow for tens of hours (Depreiter et al., 2023a, 2023b, in prep; Koelewijn et al., 2022). Furthermore, recent overflow tests at biodiverse vegetated revetments indicate such species-rich river dike vegetation covers are extremely erosion resistant (Liebrand et al., in prep).

The erosion pattern during the extreme tests indicates the joints between individual sods are a weak spot. Similar erosion at joints was observed during a comparable lab model overflow test by Scheres and Schüttrumf (2020). Although they did not transplant sods, they did have joints in their simulated dike. To ensure a more erosion resistant transplanted sod revetment, the joints between sods need to be minimized. For instance, by better sealing with clay or applying an additional (temporary) reinforcement such as a geogrid (Scheres & Schüttrumf, 2020).

Experiments by others with sown vegetated dike covers also showed erosion. In a lab experiment, wave impact and overflow eroded parts of an experimental dike cover 6 and 18 months after sowing a species-poor grass-dominated reference mixture (Scheres & Schüttrumf, 2020). Wave impact led to erosion depths up to at least 0.15 m (tests stopped at this depth). In comparison, an experimental dike revetment still showed erosion due to rainfall 2–3 years after sowing grass species (Berendse et al., 2015).

4.2 | Locally sourced materials around the managed realignment site

In this study we explored the use of locally sourced materials for realigned dikes. Local material can be more sustainable and less expensive, due to the proximity to the construction site. Local, autogenous sediment and vegetation is also preferred from an ecological perspective. Of course, the locally sourced materials need to be of sufficient quality. This is currently also investigated for example within the projects 'POV dike reinforcement with local soil' and 'Clay ripening pilot'. In general, construction material for the realigned dike can be locally sourced from three places: old seaward dike, former hinterland, and foreshores.

The first local source is the old seaward dike, which we also used in our in-situ experiment. The old seaward dike is usually prepared for realignment by either breaching, lowering, removing, or installing culverts or sluices (Esteves, 2014c). This old dike can hereby provide sediment and vegetation, and there are numerous examples where it provided sediment (clay and sand) for the new dike in managed realignments. Amongst others at the Hedwige-Prosperpolder and Lillo Potpolder (van den Hoven et al., 2022). The old dike can also be a source of erosion resistant vegetation.

The second source is the former hinterland. In the past, clay for the landward realigned dike has been dug from the former hinterland in lanes (at least along the Southern Dutch coast (Kuipers & Jacobusse, 1998). Now, preparations for tidal inundation such as digging creeks or levelling elevation can provide sediment for the realigned dike (van den Hoven et al., 2022). In addition, vegetation from the hinterland can be suitable for the landside dike slope. In line with recent publications on double dike (managed realignment) systems (van Belzen & Bouma, 2021; Weisscher et al., 2022), we propose to use the area in between two dikes as a dike vegetation nursery. This is similar to dune vegetation production on German Wadden Islands.

The third source is foreshores such as saltmarshes. These can be the existing, often high, elevated foreshores fronting the old dikes. Additionally, clay can be mined from foreshores pits, which refill over time where there is an abundant sediment supply (Marijnissen et al., 2020). Sod removal from natural saltmarshes may seem an unnecessary disturbance to nature, but it has several advantages. Sod removal can rejuvenate climax saltmarshes, for example of Sea Couch (*Elytrigia atherica*), into earlier vegetation stages with a larger flora and fauna biodiversity yield (de Leeuw et al., 1992; Smits et al., 2014a). Many examples can be found in The Netherlands along the Eastern Scheldt (de Leeuw et al., 1992; Kuipers & Jacobusse, 1998) and Western Scheldt Estuary (e.g., Voorland Nummer Één). Sod removal can hereby assist nature restoration and biodiversity increase within the European Natura 2000 framework (Smits et al., 2014a, 2014b). Nature restoration can be seen as compensation for possible damage incurred by dike reinforcements. In relation to managed realignment there is a practical advantage. Sod removal lowers the elevation of high elevated foreshores that would otherwise limit water flow into the realignment site (van den Berg et al., in prep; Schoutens et al., 2022).

4.3 | Recommendations beyond our living lab and study limitations

As far as we are aware our study is the first scientific attempt to test the sods transplantation technique. Our in-situ experiment can hereby be seen as a Dutch dike case study. For further research we recommend investigating the sods transplantation technique in different settings and with different vegetation. For instance in another field lab or as part of a dike reinforcement pilot. It will be interesting to compare our results to sods varying in size and thickness. Thinner sods will be harder to harvest but they probably better connect to the dike.

Our study contributes to the practical application of sod transplantation. Sods from local vegetation sources can be transplanted to newly constructed dikes. Floodplain sods might be suitable for river dike revetments. Foreshore sods may be useful to introduce saline tolerant species at the dike toe and to create an ecological gradient between the foreshore and dike. Sods transplantation can also be used to adapt an existing dike revetment. Either to change from a non-vegetated into a vegetated revetment, to adjust the vegetation, or to heighten the dike step by step as each sods layer adds sediment. At

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regular dike reinforcements the old revetment can be reused. This is already done for instance at the Canadian East coast (*Pers. comm.* C. Ross & M. Graeme Nova Scotia Department of Agriculture). Sods can also be a temporary fix in emergency dike repair, as was historical common practise. In addition, transplanting sods might be a faster way to create a vegetated revetment that is resistant to droughts, due to the existing roots. Furthermore, our experiment with sod transplantation could inspire future managed realignments. For instance; within the Shoreline Management Plans in the UK (e.g., in Wales, Buser, 2020), as part of the Belgian Sigma Plan (FWA, 2006), or with the tidal river management approach in Bangladesh (e.g., Gain et al., 2022). In double dike managed realignments, the area between the two dikes can serve as a dike vegetation nursery.

Our experimental set-up had some limitations. Maintenance differed slightly between the plots. The mowing regime was limited (Table S2) due to unforeseen circumstances and because we wanted to investigate the vegetation species. Reduced mowing might have influenced the transplanted sods rooting capacity. In addition, root development into the original dike was possibly restrained due to sufficient nutrient supply within the sods and underlying damaged vegetation layer. Furthermore, one can argue we could have used a different reference setting, namely a newly sown revetment. We wanted, however, to compare the transplanted sods strength with the desired strength of a well-developed revetment at the same dike. Dike managers already consider a newly sown vegetated revetment is not erosion resistant after one growth season (Muijs, 1999). For further research we recommend comparing a transplanted sod revetment with a newly sown dike revetment and a bare revetment. Our results could be compared to future experimental results with sown dike revetments, such as at the Dutch Wadden Sea dikes where the revetment strength is being explored of newly sown plots with different species compositions (Grashof-Bokdam et al., in prep).

We are aware part of the data collection had a limited sample size. This in part was owing to the methodology as, for instance, the simulation of extreme hydraulic conditions is costly, demanding, and destructive. We can compare the wave impact and overflow results to other studies (Section 4.2). The sod pulling method had a relatively small sample size ($n = 15$), so we determined a critical t-value related to the lower sample size. Other studies used a critical t-value related to unlimited degrees of freedom (1.96, Daamen et al., 2023). With the value of 1.96 the critical flow velocity would have been 0.1 m/s higher (9.9 and 7.0 m/s instead of 9.8 and 6.9 m/s respectively). Nonetheless, our results give valuable insights in the strength of a transplanted dike sod revetment.

5 | CONCLUSION

Coastal flood managers seek to anticipate future flood risk in a changing coastal environment. Flood infrastructure such as dikes need to be adapted to face future flood risk challenges. In this study, we focussed on the adaptation of coastal dikes. Flood protection by dikes can be adapted by integrating vegetated foreshores. For instance, at managed realignment sites the realigned dike and vegetated foreshores can be combined in a hybrid nature-based flood defence. We are aware managed realignment comes with trade-offs for previous land-use functions, and we advise to carefully include local stakeholders and compensate landowners (Schuerch et al., 2022). In this study, we researched managed realignments in a flood protection and ecological perspective. Because realigned dikes are not automatically prepared for a sound connection with restored foreshores, we propose to prepare the realigned dike for this connection through a vegetated revetment. A vegetated dike revetment hereby creates a more natural and continuous connection that benefits flood protection, as well as flora and fauna.

The creation of an erosion resistant vegetated revetment can take up to 5 years. In this study, we investigated a faster way by using locally sourced material. We applied the historic sod transplantation technique, which can provide sediment and vegetation to create a vegetated dike revetment. Simultaneously, sod mining from former land or saltmarshes can support intertidal nature restoration and development. Our aim was to improve our understanding of the strength of a transplanted dike grass sod revetment. In Living Lab Hedwige-Prosperpolder the dike was available for research because it had to be removed as part of a managed realignment. We used these unique circumstances as an opportunity to set up an in-situ experiment and perform wave impact and overflow simulations. Our results showed after one growth season the transplanted sod revetment was weaker than the well-developed reference revetment. However, the transplanted sods did start to attach to the dike clay layer and the sod pulling method estimated the critical flow velocity value of individual sods was above the Dutch dike standards. In conclusion, sod transplantation is a good technique to source local material for green realigned dike revetments.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Zenodo with doi: 10.5281/zenodo.8089587. The videos of this study are openly available in Zenodo with doi: 10.5281/zenodo.8146722.

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REFERENCES

Bartels, M. H. (2017). de Westfriese omringdijk, archeologisch en historisch onderzoek tussen Hoorn en Enkhuizen, Archeologie in Nederland 2, 34–41.

Bax, V. W. I., van de Lageweg, T., Terpstra, J.-M., de Buijs, K., de Reus, F., van Groot, R., Schaik, M. A., Habte, J., & Schram, T. H. (2023). The impact of coastal realignment on the availability of ecosystem services: Gains, losses and trade-offs from a local community perspective. *Journal of Environmental Management*, *345*, 118675. https://doi.org/10.1016/j.jenvman.2023.118675

Bazelmans, J., Gerrets, D., de Koning, J., & Vos, P. (1999). Zoden aan de dijk: kleinschalige dijkbouw in de late prehistorie en protohistorie van noordelijk Westergo. *de Vrije Fries*, *79*(1999), 7–74.

Beeftink, W. G. (1975). The ecological significance of embankment and drainage with respect to the vegetation of the south-west Netherlands. *Journal of Ecology*, *63*(2), 423–458.

Berendse, F., Ruijven, V., Jongejans, E., & Keesstra, S. (2015). Loss of plant species diversity reduces soil erosion resistance. *Ecosystems*, *18*, 881–888. https://doi.org/10.1007/s10021-015-9869-6

Bijlard, R. (2015). Strength of the grass sod on dikes during wave overtopping. [MSc thesis, Delft University of Technology] http://resolver.tudelft.nl/uuid:bd2c6618-3143-45d3-8bd9-f24c76e7d8ae

Bijlard, R., Steendam, G. J., Verhagen, H. J., & van der Meer, J. (2017). Determining the critical velocity of grass sods for wave overtopping by a grass pulling device. *Coastal Engineering Proceedings*, *1*(35), 20. https://doi.org/10.9753/icce.v35.structures.20

Bridges, T. S., King, J. K., Simm, J. D., Beck, M. W., Collins, G., Lodder, Q., & Mohan, R. K. (Eds.). (2021). *International guidelines on natural and nature-based features for flood risk management*. U.S. Army Engineer Research and Development Center.

Bridges, T. S., Smith, J. M., King, J. K., Simm, J. D., Dillard, M., de Vries, J., Reed, D., Piercy, C. D., van Zanten, B., Arkema, K., Swannack, T., de Looff, H., Lodder, Q., Jeuken, C., Ponte, N., Gailani, J. Z., Whitfield, P., Murphy, E., Lowe, R. J., … Naylor, L. A. (2022). Coastal natural and nature-based features: International guidelines for flood risk management. *Frontiers in Built Environment*, *8*, 904483. https://doi.org/10.3389/fbuil.2022.904483

Brown, S., Jenkins, K., Goodwin, P., Lincke, P. D., Vafeidis, A. T., Tol, R. S. J., Jenkins, R., Warren, R., Nicholls, R. J., Jevrejeva, S., Sanchez Arcilla, A., & Haigh, I. D. (2021). Global costs of protecting against sea-level rise at 1.5 to 4.0°C. *Climatic Change*, *167*, 4. https://doi.org/10.1007/s10584-021-03130-z

Buser, M. (2020). Coastal adaptation planning in Fairbourne, Wales: Lessons for climate change adaptation. *Planning Practise & Researh*, *35*(2), 127–147. https://doi.org/10.1080/02697459.2019.1696145

CIRIA. (2013). The International Levee Handbook. C731 CIRIA RP957. CIRIA, ISBN 978-0-86017-734-0, p.1332.

Daamen, E., Heida, L., Mom, R., & Wauben, C. (2023). Factual report golfoverslag- en grastrekproeven Polder2C's. Version: 20230329. https://polder2cs.eu/results/reports/flood-defence

Daamen, E., Heida, L., & Wauben, C. (2022). Factual report golfklapproeven. Versie: 3.0, 19 juli 2022. https://doi.org/10.5281/zenodo.8089587

de Leeuw, J., Apon, L. P., Herman, P. M. J., de Munck, W., & Beeftink, W. G. (1992). Vegetation response to experimental and natural disturbance in two salt-marsh plant communities in the Southwest Netherlands. *Netherlands Journal of Sea Research*, *30*, 279–288.

Depreiter, D., Vercruysse, J., Verelst, K., Zomer, W., Koelewijn, A. R., Tsimopoulou, V., & Peeters, P. (2023a). Continuous overflow tests on Belgian levees. Version: 1.0 – 20221115. 103 pp.

Depreiter, D., Vercruysse, J., Verelst, K., Zomer, W., Koelewijn, A. R., Tsimopoulou, V., & Peeters, P. (2023b). Overflow tests on Dutch levees. Version: 1.0 – 20221222. 110 pp.

Depreiter, D., Verelst, K., Vercruysse, J., Koelewijn, A. R., Zomer, W., & Peeters, P. (in prep). Full-scale steady overflow tests on grass covered levees and impact of surface anomalies on damage development. TUD Journal of Coastal and Riverine Flood Risk.

Esteves, L. S. (2014a). *Managed realignment: A viable long-term coastal management strategy?* SpringerBriefs in Environmental Science. https://doi.org/10.1007/978-94-017-9029-1

Esteves, L. S. (2014b). The need for adaptation in coastal protection: Shifting from hard engineering to managed realignment. In L. S. Esteves (Ed.), *Managed realignment: A viable long-term coastal management strategy?* (pp. 1–18). Springer Netherlands. https://doi.org/10.1007/978-94-017-9029-1_1

Esteves, L. S. (2014c). Methods of implementation. In L. S. Esteves (Ed.), *Managed realignment: A viable long-term coastal management strategy?* (pp. 33–44). Springer Netherlands. https://doi.org/10.1007/978-94-017-9029-1_3

French, P. W. (2006). Managed realignment—the developing story of a comparatively new approach to soft engineering. *Estuarine, Coastal and Shelf Science*, *67*(3), 409–423. https://doi.org/10.1016/j.ecss.2005.11.035

FWA, Flemisch Waterways Administration. (2006). *Geactualiseerd Sigmaplan voor Veiligheid en Natuurlijkheid in Het Bekken van de Zeeschelde:Synthesenota*. Antwerpen, Belgium.

Gain, A. K., Mofizur Rahman, M., Shibly Sadik, M., Adnan, M. S. G., Ahmad, S., Ahsan, S. M. M., Ashik-Ur-Rahman, M., Balke, T., Datta, D. K., Dewan, C., Huq, N., Khan, M. S. A., Large, A., Mallick, B., Mohibbulla, M., Mondal, M. S., Narayan, S., Rabbani, G., Rahman, R., … van Loon-Steensma, J. M. (2022). Overcoming challenges for implementing naturebased solutions in deltaic environments: Insights from the Ganges-Brahmaputra delta in Bangladesh environ. *Research Letters*, *17*, 064052. https://doi.org/10.1088/1748-9326/ac740a

Gerritsen, S. (2016). Wonen op een middeleeuwse dijkdoorbraak. Onderzoek naar de Klamdijk en de nederzetting Lutjeschardam. In *Archeologie in West-Friesland 19*. Archeologie West-Friesland, Hoorn. ISSN 2212-4365.

Grashof-Bokdam, C., van Rooijen, N., Visser, E. J. W., & van der Zee, F. (in prep). Gras- en kleibekleding waddenzeedijken, Fase D. Monitoring proefvlakken gras/kruidenmengsels. Eindrapportage. Wageningen Environmental Research, Wageningen.

Hinkel, J., Lincke, D., Vafeidis, A. T., Perrette, M., Nicholls, R. J., Tol, R. S. J., Marzeiong, B., Fettweish, X., Ionescuc, C., & Levermann, A. (2014). Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proceedings of the National Academy of Sciences*, *111*(9), 3292–3297. https://doi.org/10.1073/pnas.1222469111

Hochard, J. P., Barbier, E. B., & Hamilton, S. E. (2021). Mangroves and coastal topography create economic "safe havens" from tropical storms. *Scientific Reports*, *11*, 15359. https://doi.org/10.1038/s41598-021-94207-3

Hoffmans, G. J. C. M. (2012). *The influence of turbulence on soil erosion*. Eburon.

IPCC. (2019). IPCC special report on the ocean and cryosphere in a changing climate. In H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, & N. M. Weyer (Eds.), (pp. 321–445). Cambridge University Press. https://doi.org/10.1017/9781009157964.006

IPCC. (2022). Point of departure and key concepts. In: Climate change 2022: Impacts, adaptation and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change. In H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama (Eds.), (pp. 121–196). Cambridge University Press. https://doi.org/10.1017/9781009325844.003

Jorissen, R., Kraaij, E., & Tromp, E. (2016). Dutch flood protection policy and measures based on risk assessment. *E3S Web of Conferences*, *7*, 2016. https://doi.org/10.1051/e3sconf/2016

Kirwan, M. L., Temmerman, S., Skeehan, E. E., Guntenspergen, G. R., & Fagherazzi, S. (2016). Overestimation of marsh vulnerability to sea level rise. *Nature Climate Change*, *6*, 253–260. https://doi.org/10.1038/NCLIMATE2909

Koelewijn, A. R. S. J. H., Rikkert, P., Peeters, D., van Depreiter, M., & Damme, W. Z. (2022). Overflow tests on grass-covered embankments at the living lab Hedwige-Prosperpolder: An overview. *Water*, *2022*(14), 2859. https://doi.org/10.3390/w14182859

Kuipers, J. J. B., & Jacobusse, C. (1998). *Het Zeeuwse monument* (p. 72). Inlagen en Karrevelden.

Liebrand, C., van Rooijen, N., Evers, M., Mom, R., & van Hoven, A. (in prep). Rapportage Future Dikes Thema 0 Huidige kennis.

Marijnissen, R., Esselink, P., Kok, M., Kroeze, C., & van Loon-Steensma, J. M. (2020). How natural processes contribute to flood protection—A sustainable adaptation scheme for a wide green dike. *Science of the Total Environment*, *139698*, 139698. https://doi.org/10.1016/j.scitotenv.2020.139698

Mazda, Y., Magi, M., Ikeda, Y., Kurokawa, T., & Asano, T. (2006). Wave reduction in a mangrove forest dominated by Sonneratia sp. *Wetlands Ecology and Management*, *14*, 365–378.

Möller, I., Kudella, M., Rupprecht, F., Spencer, T., Paul, M., van Wesenbeeck, B. K., Wolters, G., Jensen, K., Bouma, T. J., Miranda-Lange, M., & Schimmels, S. (2014). Wave attenuation over coastal salt marshes under storm surge conditions. *Nature Geoscience*, *7*(10), 727–731. https://doi.org/10.1038/ngeo2251

Mooyaart, L. F., Bakker, A. M. R., van den Bogaard, J. A., Rijcken, T., & Jonkman, B. (2023). Economic optimization of coastal flood defence systems including storm surge barrier closure reliability. *Journal of Flood Risk Management*, *16*(3), e12904. https://doi.org/10.1111/jfr3.12904

Muijs, J. A. (1999). Grass cover as a dike revetment. Technical Advisory Committee for Flood Defence (TAW).

Muijs, J. A., & Sprangers, J. T. C. M. (1997). Groene Zeedijken in Noord-Duitsland en Denemarken. Verslag van een studiereis 3-7 juni 1991. Delft, W-DWW-97-003.

MVW, Ministerie van Verkeer en Waterstaat. (2007). *Voorschrift Toetsen op Veiligheid Primaire Waterkeringen*. Iov.

Nicholls, R. J., Lincke, D., Hinkel, J., Brown, S., Vafeidis, A. T., Meyssignac, B., Hanson, S. E., Merkens, J.-L., & Fang, J. (2021). A global analysis of subsidence, Relative Sea-level change and coastal flood exposure. *Nature Climate Change*, *11*, 338–342. https://doi.org/10.1038/s41558-021-00993-z

Pontee, N. I. (2013). Defining coastal squeeze: A discussion. *Ocean & Coastal Management*, *84*, 204–220. https://doi.org/10.1016/j.ocecoaman.2013.07.010

RWS, Rijkswaterstaat Water Verkeer en Leefomgeving. (2022). Schematiseringshandleiding grasbekleding, 6.0, 31 maart 2022. Ministerie van Infrastructuur en Waterstaat.

Scheres, B., & Schüttrumf, H. (2020). Investigating the erosion resistance of different vegetated surfaces for ecological enhancement of sea dikes. *Journal of Marine Science and Engineering*, *8*, 519. https://doi.org/10.3390/jmse8070519

Schippers, M., van Hoven, A., Mom, R., de Kroon, H., van Rooijen, N., Visser, E. J. W., & Grashof-Bokdam, C. J. (2018). Gras- en kleibekleding: Inhoudelijke rapportage Fase B.

Schoonees, T., Gijón Mancheño, A., Scheres, B., Bouma, T. J., Silva, R., Schlurmann, T., & Schüttrumpf, H. (2019). Hard structures for coastal protection, towards greener designs. *Estuaries and Coasts*, *42*(7), 1709–1729. https://doi.org/10.1007/s12237-019-00551-z

Schoutens, K., Stoorvogel, M. M., van den Berg, M., van den Hoven, K., Bouma, T. J., Aarninkhof, S., Herman, P. M. J., van Steensma, J. M. L., Meire, P., Schoelynck, J., Peeters, P., & Temmerman, S. (2022). Stability of a tidal marsh under very high flow velocities and implications for nature-based flood defense. *Frontiers in Marine Science*, *9*, 920480. https://doi.org/10.3389/fmars.2022.920480

Schuerch, M., Mossman, H. L., Moore, H. E., Christie, E., & Kiesel, J. (2022). Invited perspectives: Managed realignment as a solution to mitigate coastal flood risks—Optimizing success through knowledge co-production. *Natural Hazards and Earth System Sciences*, *22*, 2879–2890. https://doi.org/10.5194/nhess-22-2879-2022

Simm, J., Ballard, B. W., Flikweert, J.-J., van Maren, E., Dimakapoulos, A., Kinnear, R., Arthur, M., Tourment, R., Neutz, C., & van Steeg, P. (2021). Investigation, assessment and remediation of levee transitions. In *FLOODrisk 2020-4th European Conference on Flood Risk Management*. Budapest University of Technology and Economics (BME). https://doi.org/10.3311/FloodRisk2020.14.6

Smits, N. A. C., Slim, P. A., & van Dobben, H. F. (2014a). *Herstelstrategie H1330A: Schorren en zilte graslanden (buitendijks)*. Ministerie van Landbouw.

Smits, N. A. C., Slim, P. A., & van Dobben, H. F. (2014b). *Herstelstrategie H1330B: Schorren en zilte graslanden (binnendijks)*. Ministerie van Landbouw.

Sprangers, J. T. C. M., & Arp, W. A. (1999). *Toetsingsparameter dijkgrasland—indicatorsoorten dijkgraslandtypen en worteldichtheidbepalingen (handmethode)*. Wageningen.

Steendam, G. J. (2017). Eisen Grasbekledingen. Projectnummer: 17i394. Versie 2.0. INFRAM B.V.

Sutton-Grier, A. E., Wowk, K., & Bamford, H. (2015). Future of our coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. *Environmental Science & Policy*, *2015*(51), 137–148. https://doi.org/10.1016/j.envsci.2015.04.006

Temmerman, S., Meire, P., Bouma, T. J., Herman, P. M. J., Ysebaert, T., & de Vriend, H. J. (2013). Ecosystem-based coastal defence in the face of global change. *Nature*, *504*(7478), 79–83. https://doi.org/10.1038/nature12859

van Belzen, J. G. U. R., & Bouma, T. J. (2021). *Dubbele dijken als robuuste waterkerende landschappen voor een welvarende Zuidwestelijke Delta*. NIOZ Report 2021-01. (p. 99). NIOZ Royal Netherlands Institute for Sea Research. https://doi.org/10.25850/nioz/7b.b.kb

van Bergeijk, V. M., Warmink, J. J., & Hulscher, S. J. M. H. (2022). The effects of transitions in cover type and height on the wave overtopping load on grass-covered flood defences. *Applied Ocean Research*, *125*, 103220. https://doi.org/10.1016/j.apor.2022.103220

van den Berg, M., Rikkert, S., Aarninkhof, S., & Labeur, R. J. (in prep). Assessment of in-situ tidal marsh erodibility under high flow velocities.

van den Hoven, K. (2023). Videos for: Greening the dike revetment with historic sod transplantation technique in a living lab. Zenodo, Version 1.0. [Videos] https://doi.org/10.5281/zenodo.8146722

van den Hoven, K., Baaij, B. M., Grashof-Bokdam, C. J., Slim, P. A., Depreiter, D., Koelewijn, A. R., Peeters, P., & van Loon-Steensma, J. M. (2023). Data for: Greening the dike revetment with historic sod transplantation technique in a living lab. Zenodo, Version 1.0. [Data set] https://doi.org/10.5281/zenodo.8089587

van den Hoven, K., Kroeze, C., & van Loon-Steensma, J. M. (2021). How about the dikes? Managed realignment in progress at the Hedwige-Prosperpolder. *Proceedings of FLOODrisk 2020—4th European Conference on Flood Risk Management* https://doi.org/10.3311/FLOODRisk2020.14.13

van den Hoven, K., Kroeze, C., & van Loon-Steensma, J. M. (2022). Characteristics of realigned dikes in coastal Europe: Overview and opportunities for nature-based flood protection. *Ocean and Coastal Management*, *22*, 106116. https://doi.org/10.1016/j.ocecoaman.2022.106116

van den Hoven, K., van Belzen, J., Kleinhans, M. G., Schot, D. M. J., Merry, J., van Loon-Steensma, J. M., & Bouma, T. J. (2023). How natural foreshores offer flood protection during dike breaches: An explorative flume study. *Estuarine, Coastal and Shelf Science.*, *294*, 108560. https://doi.org/10.1016/j.ecss.2023.108560

van Loon-Steensma, J. M., & Kok, M. (2016). Risk reduction by combining nature values with flood protection? *E3s Web of Conferences*, *7*, 13003. https://doi.org/10.1051/e3sconf/20160713003

van Loon-Steensma, J. M., Slim, P. A., Vroom, J., Stapel, J., & Oost, A. P. (2012). Een Dijk van een Kwelder. Een verkenning naar de golfreducerende werking van kwelders. Alterra-rapport 2267. Alterra, onderdeel van Wageningen UR, Wageningen.

van Steeg, P., Klein Breteler, M., & Labrujere, A. (2014). Use of wave impact generator and wave flume to determine strength of outer slopes of grass dikes under wave loads. Proceedings 34th Conf. Coastal Eng., Seoul, Korea, 15–20 June 2014.

van Wesenbeeck, B. K., Wolters, G., Antolínez, J. A. A., Kalloe, S. A., Hofland, B., de Boer, W. P., Çete, C., & Bouma, T. J. (2022). Wave attenuation through forests under extreme conditions. *Scientific Reports*, *12*, 1884. https://doi.org/10.1038/s41598-022-05753-3

van Zelst, V. T. M., Dijkstra, J. T., van Wesenbeeck, B. K., Eilander, D., Morris, E. P., Winsemius, H. C., Ward, P. J., & de Vries, M. B. (2021). Cutting the costs of coastal protection by integrating vegetation in flood defences. *Nature Communications*, *12*, 6533. https://doi.org/10.1038/s41467-021-26887-4

Vandevoorde, B., & van Lierop, F. (2021). T0-bepaling van de dijkvegetatie Hedwige-Prosperpolder (datarapport). Rapporten van het Instituut voor Natuur- en Bosonderzoek jaar 2021 (60). Instituut voor Natuur- en Bosonderzoek, Brussel https://doi.org/10.21436/inbor.70310631

Vercruysse, J., Depreiter, D., López Castaño, S., Verelst, K., & Peeters, P. (2023). Design and application of an overflow generator. Version: 20230424. WL2023R20_047_1.

Vousdoukas, M. I., Mentaschi, L., Hinkel, J., Ward, P. J., Mongelli, I., Ciscar, J.-C., & Feyen, L. (2020). Economic motivation for raising coastal flood defenses in Europe. *Nature Communications*, *11*(1), 2119. https://doi.org/10.1038/s41467-020-15665-3

Vuik, V., Jonkman, S. N., Borsje, B. W., & Suzuki, T. (2016). Nature-based flood protection: The efficiency of vegetated foreshores for reducing wave loads on coastal dikes. *Coastal Engineering*, *116*, 42–56. https://doi.org/10.1016/j.coastaleng.2016.06.001

Vuik, V., van Vuren, B., Borsje, B. W., van Wesenbeeck, B., & Jonkman, S. N. (2018). Assessing safety of nature-based flood defenses: Dealing with extremes and uncertainties. *Coastal Engineering*, *139*, 47–64.

Waterloopkundig Laboratorium. (1984). Verslag van het buitenbeloop van een 'groene dijk' tijdens een superstormvloed. Onderzoek van een met gras begroeide dijk langs de Fries Waddenkust, tussen de Noorderleegpolder en Holwerd. Verslag Grootschalig Modelonderzoek. Rapport Waterloopkundig Laboratorium.

Weisscher, S. A. H., Baar, A. W., van Belzen, J., Bouma, T. J., & Kleinhans, M. G. (2022). Transitional polders along estuaries: Driving land-level rise and reducing flood propagation. *Nature-Based Solutions*, *2*, 100022. https://doi.org/10.1016/j.nbsj.2022.100022

Willemsen, P. W. J. M., Borsje, B. W., Vuik, V., Bouma, T. J., & Hulscher, S. J. M. H. (2020). Field-based decadal wave attenuating capacity of combined tidal flats and salt marshes. *Coastal Engineering*, *156*, 103628. https://doi.org/10.1016/j.coastaleng.2019.103628

Zhu, Z., Vuik, V., Visser, P. J., Soens, T., van Wesenbeeck, B. K., van de Koppel, J., Jonkman, S. N., Temmerman, S., & Bouma, T. J. (2020). Historic storms and the hidden value of coastal wetlands for nature-based flood defence. *Nature Sustainability*, *3*(10), 853–862. https://doi.org/10.1038/s41893-020-0556-z

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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