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Dendrochronology of Ancient Pine Trunks Exposed at the Coastal Bluff: Dating Problems and Possible Causes

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Coastal erosion and slumping of the coastal bluff occur at the present day along certain stretches of the Baltic Sea coastal belt in western Latvia. The coast currently being eroded is regarded as consisting partly of a cover of wind-blown sand formed 250–300 years ago, a period that saw intensive landward aeolian sand transport as a result of forest cutting and forest fires in the coastal belt and other factors relating to human activity. Within the frame of a short-term research project, dendrochronological dating work was undertaken on remnants of pine trunks discovered at various locations on the coastal bluff that appeared to be remains of ancient trees exposed by erosion, with the aim of determining where and when these natural processes had occurred. This study did not succeed in demonstrating dendrochronologically that the apparently ancient tree trunk remnants observable along certain stretches of the coast at the present day are remains of pines buried by sand more than 250 years ago. It has been established that certain of these are remnants of pines that died in the 20th century or even just a few years ago, but in the majority of cases an unambiguous old date could not be obtained. In order to ascertain the possible reasons why dendro-dating had produced such limited results, in the further part of the study a comparison was undertaken of the patterns of variation in annual radial trunk growth of pines growing in the dune belt along the whole of the Latvian seaboard at the present day. Also considered are the previous findings of short-term studies in all three Baltic States concerning the influence of specific environmental factors on the radial growth of pine. It has been established that the reasons why dendro-dating was problematic relate to the specific character and variation in the environmental factors significantly affecting tree growth, as well as the slope processes on the coastal bluffs. It is envisaged that the findings obtained and brought together in this study will be useful in future, when undertaking or planning dendro-dating work for the purpose of tracing the history of dune migration or assessing the radial growth of pines growing in dunes.

Keywords: dendrochronology, coast of Latvia, Scots pine, remains of ancient pine trunks, dunes and dune migration, environmental factors

INTRODUCTION

Coastline retreat, through the erosion and collapse of coastal bluffs, is a process observable at the present day along certain stretches of the Baltic Sea coast of western Latvia (Eberhards, 2003, 2004), and is becoming more pronounced due to changes in the natural environment as well as human activities, which are increasingly impacting on natural processes. With a rise in air temperature, the likelihood, frequency, and duration of sea ice and frozen ground in winter have decreased, progressively shortening the period when the coast is protected from strong wind and water action (Eberhards, 2003). Moreover, coastal erosion is exacerbated on the downdrift side of hydrotechnical constructions along the Latvian coast, which interrupt the natural longshore sediment flow (Eberhards, 2004).

There is reason to believe that the coast being eroded at the present-day partially consists of a covering deposit of sand formed approximately 250–300 years ago. The transport of sand by the wind, and thus also the landward movement of dunes, was the direct result of the destruction of coastal forests. They were cut on a large scale in this period for the needs of shipbuilding and newly developed industries and burned down during the Northern War (1700–1721). The second half of the 18th century saw extensive destruction of forests along the eastern shore of the Baltic Sea's Gulf of Riga because of tar production for the needs of the Russian fleet (Bušs, 1960). The extent of dune migration is also reflected in accounts of how they gradually buried tree stumps in the forest cuttings as well as the trunks of standing trees, rivers, fields and farms near the coast, and at least in a few cases manor-houses and churches as well (Sarma, 1974; Eberhards, 2003; Stūre, 2009). Measures to halt dune migration commenced only in the first half of the 19th century, when a protective belt was established along the coast, in which further forest-cutting, collection of forest litter and burning were banned, in conjunction with large-scale stabilization and afforestation of the dunes (Sarma, 1974).

When a dune migrated landwards, it would sometimes leave flat ground in its wake, potentially revealing the remnants of previously buried forest, in the form of tree trunks, stumps or just bark cylinders remaining after decomposition of the wood (Bušs, 1960). Occasionally, however, remains of trees or even wooden artifacts once buried under the dunes have also come to light as a result of the erosion of high coasts. There is also evidence that remains of buried forests have been exposed in this way (Veldre, 1991).

Radiocarbon (^{14}C) dating indicates that in certain places under the coastal dunes of western Latvia there is preserved wood not just a few centuries old but also from much earlier periods: thus, a buried sample of pine wood from the SW Latvian coast has been dated to 127–383 calAD (**Supplementary Table 1**: Bernāti 2007), while an oak trunk likewise buried under sand in the present-day town of Jūrmala on the Gulf of Riga has been dated to 770–471 BC (**Supplementary Table 1**: Asari-1) [Conventional ^{14}C ages have been calibrated using OxCal v.4.4 (Ramsey, 2009) and the IntCal20 calibration curve (Reimer et al., 2020)].

In 2018, when the program was put together for the research project "People in a dynamic landscape: tracing the biography of Latvia's sandy coastal belt," it also included the task of dendro-dating the remains of several ancient Scots pine (*Pinus sylvestris* L.) trunks discovered on the face of the coastal bluff, presumed to have been exposed through the erosion of the covering sands. It was anticipated that this would make it possible to determine the time when they had been buried by sand, i.e., the time of dune formation or migration. This task directly corresponded to the project goal, namely to trace the main vectors and significant turning points in the long-term development of Latvia's sandy coastal belt, focusing on resource use and the interaction between human activities and the non-human forces shaping this dynamic and sensitive landscape (Bērziņš, 2021).

In the course of implementing this task, a survey was undertaken along several stretches of the coast of western Latvia with a coastal bluff or with major dunes some distance from the shore whose migration has been halted. Exposures were checked for remains of potentially ancient (subfossil) pine trunks. Such remains were discovered at several sites. However, in the course of the project it was not possible to confirm dendrochronologically that the trunk remnants exposed along stretches of the coastal bluff are remains of pines buried by dunes more than 250 years ago, or to determine more precisely the time of dune formation or migration. Such poor results are not typical in dendro-dating, and accordingly the remainder of the study was devoted to exploring the reasons behind this situation. To this end, a comparison was undertaken of the patterns of annual radial growth of living pines along several stretches of the seacoast as well as several pines that had died recently, seeking to ascertain the factors behind the significant differences in growth pattern. The main findings of previous research in Latvia as well as in Estonia and Lithuania concerning the annual growth pattern of pines in the coastal dune belt were also considered.

The rest of this article sets out the study and its results in more detail, with brief conclusions regarding specific issues involved in dendro-dating pines formerly growing in the coastal dune belt and the future potential of such studies.

MATERIALS AND METHODS

Wood Samples and Sampling Sites

Based on previously obtained information concerning various stretches of the coastal bluff in western Latvia where erosion has been particularly active and where remains of seemingly ancient pine trunks had been seen, in 2019 and 2020 a survey of the coastal bluffs was undertaken along these stretches of the coast, with a total length of 46 km (**Figure 1**). The lengths of the separate stretches of the coastline and their locations are given in **Table 1**.

The following additional information may be given concerning the surveyed stretches of the coastline, explaining why the particular stretch of the coast was included in the survey:

Coastline stretch 1 (**Figure 1**: 1). In the 1930s, many tops of tree trunks were visible, the covering sands having been eroded (Veldre, 1991); however, no such remains were found at the time of the survey.

Coastline stretch 2 (**Figure 1**: 2). The N endpoint lies opposite Ķupu dune, nowadays located c. 0.4 km inland. This is one of

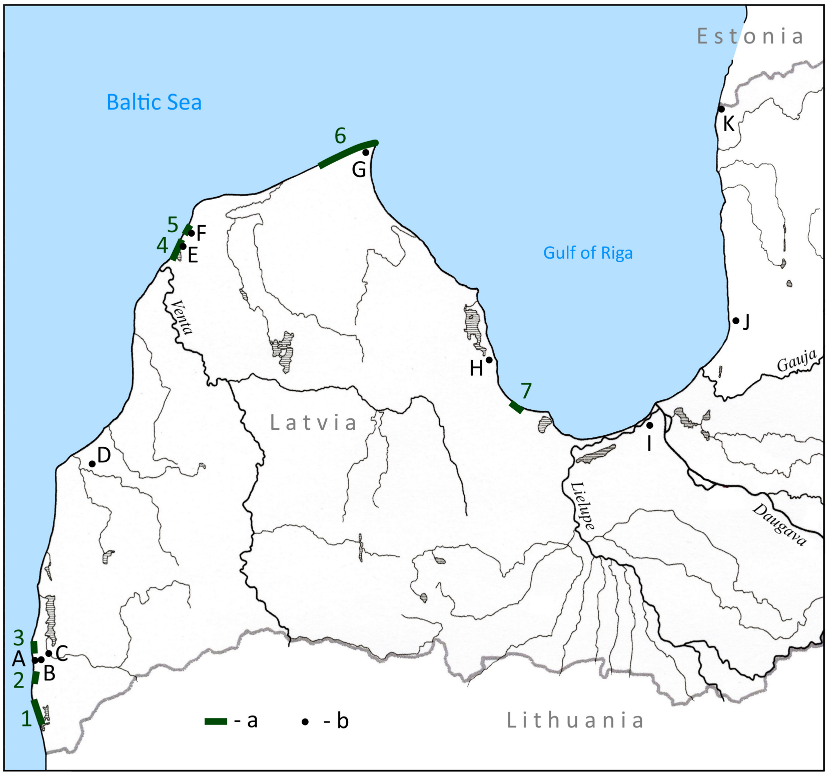

FIGURE 1 | Map of the coast of Latvia showing research sites mentioned in the text: (a) surveyed stretches of the coast; (b) sites providing the pine chronologies mentioned in the text.

Latvia's highest dunes (34 m a.s.l.), recorded as having buried a manor-house and, according to other sources, a church as well (Sarma, 1974). No remains of ancient pine trunks were recorded in the survey.

Coastline stretch 3 (**Figure 1**: 3). Here the coast has experienced major erosion. In the 1990s, a land area up to 50 m wide was lost in the course of just two storms (Eberhards, 2003). Prior to this, a storm in 1957 uncovered part of the wreck of an ancient oak ship buried under a 5 m high dune. Along this stretch of the coast, remains possibly from this same wreck were repeatedly uncovered in later years (Sudmalis, 1958; Zalsters, 1988, 1995).

At the present day, only pines that have toppled from the coastal bluff relatively recently were observed. Single core samples were obtained from six relatively large pines growing along the coastal bluff, the lower parts of the trunks of which had been partially buried by sand. In order not to harm the growing trees, along this and other investigated stretches of the coast only one core sample was obtained from each trunk. In such a situation it is much harder to identify the occurrence of missing rings or compression wood. However, when sampling the dead pines, in many cases a second core sample was taken.

Additionally, core samples were obtained from seven old pines growing on Latvia's highest dune, Pūsēnu hill. This dune, 37 m above present sea level, is nowadays located c. 540 m inland, on the site of the former Pūsēni farmstead. It first began to develop and migrate landward more than 300 years ago, after the coastal forest was cut and a large forest fire had occurred (Iltnere, 2002). Single core samples were obtained from an apparently rather old pine trunk on the steep slope of the dune and three pines growing close together at the foot of the dune.

Coastline stretch 4 (**Figure 1**: 4). This includes the geological and geomorphological natural site "Staldzene coastal bluff": an intensively eroding coastal bluff with a maximum height of almost 20 m (Eberhards, 2003). A unique artifact hoard from the Bronze Age (1500–500 BC) was recovered here in 2001 (Vasks and Vijups, 2004).

The first remains of pine trunks presumed to be ancient, in the form of several trunk remnants c. 1–2.5 m high, were found on the upper part of the coastal bluff (**Figure 2**), and the top of a stump was discovered on the beach itself. Single wood samples were sawn from the better-preserved four trunk remnants with the largest girth.

Also, in stretch no. 4, two sawn samples as well as two cores were obtained from a wooden jetty still visible at the shore, which appeared to be of some antiquity. The four piles closest to the shore were sampled. It was envisaged that the tree-ring data might be used to compile a local absolute chronology for pine, covering a period several decades ago. Additionally, at two sites along this same stretch (**Table 1**: Pine stand 1 and Pine stand 2), single core samples were obtained from five and four pines,

TABLE 1 | Stretches of the coast of western Latvia where remains of ancient tree trunks were surveyed, giving the numbers of wood samples taken (**Ø**, sawn trunk cross-section; **D**, sawn sample extending to center of trunk; **–**, core sample).

Stretch of the coast/Site No.	Name	Lat., long. of endpoints	Length (km)	Wood samples from potentially ancient pine trunks	Wood samples from living/recently dead pines	Established tree-ring chronology
1	Pape Nature Park coast	56.13757° N, 21.03395° E	8	0	0	
		56.20391° N, 20.99094° E				
2	Coast at Ķupu dune	56.24863° N, 20.98065° E	3,5	0	0	
		56.27994° N, 20.98545° E				
3	Coast at Bernāti	56.35527° N, 20.97206° E	2,5	0	6 [–]	A
		56.37758° N, 20.97583° E				
3a	W (seaward) foot of Pūsēnu hill	56.32654° N, 20.98444° E	–	0	3 [–]	B_1
3b	Pūsēnu hill	56.32674° N, 20.98627° E	–	1 [–]	7 [–]	B_2
4	Coast at Staldzene	57.41940° N, 21.57933° E	6,9	4 [Ø]		
		57.47477° N, 21.62953° E				
4a	Jetty	57.44067° N, 21.60036° E	–	2 [Ø], 2 [–]	0	
4b	Pine stand 1	57.44517° N, 21.60429° E	–	0	5 [–]	E
4c	Pine stand 2	57.45642° N, 21.61241° E	–	0	4 [–]	E
5	Coast at Liepene:	57.49362° N, 21.64649° E	2,6			
		57.51444° N, 21.66607° E				
5a	Group 1	57.49995° N, 21.65454° E	–	3 [Ø]	0	
		57.50116° N, 21.65617° E		2 [D]		
5b	Group 2	57.50604° N, 21.66175° E	–	1 [D]	0	
5c	Group 3	57.50873° N, 21.66347° E	–	1 [–]	6 [–]	
		57.51003° N, 21.66407° E		1 [Ø]		
5d	Group 4	57.51136° N, 21.66457° E	–	4 [Ø], 1 [–]	0	
5e	Five transects	57.50105° N, 21.65632° E	–	0	32 [–]	F
		57.51124° N, 21.66474° E				
6	Coast between Mazirbe and Kolka	57.68975° N, 22. 31563° E 57.75922° N, 22. 60495° E	19	10 [–]	4 [–]	G_2
7	Coast between Klapkalnciems and Apšuciems	57.05895° N, 23. 31888° E 57.04292° N, 23. 37895° E	4	5 [–]	1	
–	Kleisti forest	56.98189° N, 23.99545° E			12 [–]	I
		56.97944° N, 24.00942° E			1 [Ø]	
			Total:	37	81	

FIGURE 2 | Coastal bluff face at Liepene (stretch 5) with remnants of the trunks of apparently ancient pines (tree group 2).

respectively, these being relatively old trees growing at the coast near the present coastal bluff.

Coastline stretch 5 (**Figure 1**: 5). Here the coastal bluff is lower, but along this stretch, too, as in the above-described stretch, coastal erosion is active, as a result of the interruption of longshore sediment drift by the harbor of Ventspils (Rendenieks, 2008).

Potentially ancient trunks and stumps were discovered at four locations, mainly on the upper part of the fairly high bluff. These provided 11 sawn and 8 core samples (**Table 1**). Samples for ^{14}C dating were obtained from three of the trunk remnants in group 3.

Additionally, core samples were obtained from selected relatively old pines growing on approximately 160 m long, narrow transects oriented perpendicularly to the coastline, beginning approximately from the site of the above-mentioned pine trunk remnants and continuing landward. Transects 1 and 2 were placed relatively close together: transect 1 was opposite the middle of the zone occupied by the first (most southerly) group of trunk remnants, while transect 2 was opposite the N end of this zone. Transect 3 was placed opposite the S end of the zone occupied by the two remains of trunks of group 2; transect 4 was opposite the S end of the trunks of group 3; and transect 5 began opposite the trunk remnants of group 4. Starting from transect 1, the distances between the transects were approximately as follows: 60 m, 710 m, 330 m, and 275 m. They were laid out in an area of forest measuring approximately 1.33×0.16 km. Along the five transects, four, seven, ten, seven, and four pines, respectively, were selected for core samples, thus sampling 32 pines in all. The selected pine trees were growing in various conditions: on older coastal dunes, on steep dune slopes and between two dunes.

Coastline stretch 6 (**Figure 1**: 6). Approximately 20 years ago, several old tree stumps were noted in the beach sand along the eastern part of this stretch, closer to Cape Kolka—the headland separating the Baltic Sea from the Gulf of Riga (Eberhards, 2003). Cores were obtained from 10 of the thickest and best-preserved pine trunks in this part of the stretch, including three samples from a very deeply buried but still living pine. Additionally, single core samples were obtained along this stretch (closest to its W end) from four relatively old pines growing in different locations on the coastal bluff.

Coastline stretch 7 (**Figure 1**: 7). At the S end of this stretch, where, according to oral information, at least one short trunk remnant had been exposed from the sand, several pine trunk remnants were discovered on the steep face of the coastal bluff, which was up to 6 m high. Core samples were obtained from the remnants of five pine trunks along this stretch.

Altogether, 37 samples from apparently ancient pine trunks and from some pines buried quite deeply by sand were collected along the various surveyed stretches of the coast, together with 81 samples from living pines, the latter to be used for establishing the quality of the dendrochronological signal and for comparison (**Table 1**).

Reference Chronologies

The absolutely dated reference chronologies utilized in this study, also used to test the quality of the dendrochronological signal, are tree-ring chronologies for present-day pine stands on various sites along the Baltic Sea coast, encompassing the whole of Latvia's 498 km long seaboard (Kūle and Markots, 2018). This study utilized 13 pine chronologies for 11 sites, compiled from ring-width data of 3–62 individual trees (**Supplementary Figure 1**). Seven of these chronologies were compiled in this study: Bernāti (**Figure 1**: A), foot of Pūsēnu hill (B_1), Pūsēnu hill (B_2), Staldzene (E), Liepene (F), Kolka 2 (G_2) as well as Kleisti (I). The remaining six are previously compiled chronologies: the Saka reference (ref.) (D), Kolka 1 ref. (G_1), and Engure ref. (H) chronologies (Zunde et al., 2008); and the Nīca ref. (C), Saulkrasti ref. (J), and Ainaži ref. (K) chronologies, complied in the 1970s (Shpalte, 1978). Details of the previously and newly compiled absolute chronologies for pine with which the tree-ring widths series (TRW series) for present-day pines growing in the dune belt were compared are given in **Supplementary Figure 1**.

The TRW series of the trunk remnants were additionally tested against a number of other absolute chronologies for pine previously compiled by the author for various sites in western Latvia (Ventspils, Liepāja, Aizpute) and from other regions of the country, as well as the Klaipėda pine ref. chronology from Lithuania (unpublished; author: A. Vitas) and the pine ref. chronology for Estonia (Läänelaid and Eckstein, 2003). These chronologies together span the period from the 14th century to the present day.

Like the apparently ancient or partially buried pines discovered in the course of the survey along the coast, the pine stands close to the seacoast where the above-mentioned chronologies were obtained were growing mainly in conditions corresponding to *Cladinoso-callunosa* and *Vacciniosa* forest site types.

Preparation and Processing of Dendrochronological Data

Ring-width measurement and dendro-dating of all the wood samples was conducted at the Dendrochronological Laboratory of the Institute of Latvian History, University of Latvia. Ring-widths were measured with a precision of 0.01 mm, using a TimeTable TT59-M-100/5 ring-width measuring device (VIAS Dendrolabor, 2015) in combination with the dendro-data processing software PAST5 (SCIEM, 2014–2015). For cross-dating of TRW series, the programs COFECHA (Holmes, 1983; Grissino-Mayer, 2001), TSAP (Rinn, 1989–1996), and SAKORE V.3 (Zunde, 2001) were also utilized, and tree-ring chronologies were compiled using ARSTAN (Cook and Homes, 1996).

The width of the rings on the sawn trunk cross sections was measured in three radial directions, and cross-dating was performed using series compiled from the means of the three ring-width values thus obtained.

In order to assess the quality of the dendrochronological signal reflected in the TRW series for pines growing in the dune belt at the present day, the TRW series for all of the above-mentioned samples from living pines were compared against each other and against the 10 chronologies listed above. The *t*-value was chosen as the measure of the quality of the dendrochronological signal: it gives the significance of the correlation coefficient and thus permits evaluation of the degree of similarity between the TRW series. The *t*-value was calculated using the formula published by Baillie and Pilcher (1973).

The TSAP program, used for cross-dating TRW series, was configured in such a way that for each pair of TRW series being compared it returned the positions for which the similarity between the TRW series gave the five relatively highest *t*-values. If these five *t*-values also included a *t*-value giving the similarity between the two TRW series in synchronous position, then this was taken as the basis for characterizing the similarity between the two TRW series. However, if the *t*-value corresponding to the synchronous position was not among the five highest *t*-values, then the *t*-value was not used for characterizing the similarity of the TRW series. In such cases, its absolute value was most commonly below 2.0, and such a low value cannot be used as an indicator of the possible synchronous position of the TRW series being compared.

RESULTS

In the course of the study, no trunk remains of pines that had died as a result of dune migration occurring 250–300 years ago were identified along the surveyed stretches of the coast. Some of the dendrochronologically dated trunk remnants were remains of trees growing in the relatively recent past, but no dates more than 200 years old have so far been obtained for any of them. Judging from the position of the trunk remnants on the face of the coastal bluff and from the physical characteristics of the wood, some of these may also be thought to be remains of trees growing relatively recently, while several other trunk remnants may indeed be from older trees.

For example, the date of some partially buried living trees and tree trunk remnants along coastline stretch 5, near Liepene (**Figure 1**: 5), corresponded to the date of sampling, while a couple of the dead pines gave dates 1–2 years earlier. However, the TRW series for some other living trees and trunk remnants located adjacent to one another or nearby differed significantly from one another and from the TRW series of the dated pines, as well as from the series of mean values of the data from these TRW series. Significantly, even though several pine trunk remnants had a large number of rings, their relative date could not be ascertained. This unexpected result suggested that some of the investigated trunk remnants might relate not only to pines growing in different periods but also to trees growing simultaneously whose year-to-year variation in radial growth reflects specific local factors. This hypothesis was tested by comparing the pattern of change in annual radial growth among pines growing in the coastal dune belt at the present day.

Dendro-Dating of Living Trees

The 81 samples from pines growing in present-day stands had from 47 up to 265 annual rings, 68 of the samples having more than 80 rings.

When the TRW series for the living trees in synchronous arrangement were compared among themselves (giving a total of 3,240 pairwise comparisons), in only about 27% of these pairwise comparisons was the *t*-value for the synchronous arrangement of the TRW series among the five highest *t*-values obtained in the respective comparison. This means that in approximately 73% of cases the similarity between the pairs of TRW series being compared was rated lower in the synchronous position than in at least five other (non-synchronous) positions. There are some exceptions, namely seven pines growing on Pusēnu hill (**Table 1**: No. 3b), six growing at Bernāti (No. 3) and five at Staldzene (No. 4b): comparison among the pines growing at each of these sites did show a significantly similar pattern of annual radial growth. The mean of the t-values included in the above-mentioned 27% of pairwise comparisons is only 3.23, although the maximum is as high as 9.4.

A definite tendency whereby individual trees growing close together show a prevailing similarity in their pattern of annual radial growth could not be observed. Such a tendency was seen more clearly when comparing the calculated degree of similarity between the patterns of annual radial growth of all the living pines with the degree of similarity exhibited by pines growing within a relatively small area of the dunes. This is also seen from the pattern of annual radial growth of the 32 selected pines along the five transects in the Liepene area (No. 5e): in 42.3% of the total of 496 pairwise comparisons between TRW series a t-value for similarity in synchronous position was returned, i.e., this t-value was among the five highest t-values (**Supplementary Table 2**).

Among the 32 sampled pines along the transects, 12 trees gave TRW series not showing a significant degree of similarity to the TRW series for any of the other 31 trees (taking a t-value > 5.0 as indicating a significant degree of similarity). The TRW series for the remaining 20 trees showed a significant degree of similarity with one to four (in one case as many as six) other TRW series for trees of this group. It is noteworthy that a significant degree of similarity in the pattern of radial growth was more commonly found not between trees on the same transect but between trees on different transects. A degree of similarity indicated by a t-value > 5.0 was less commonly obtained in comparisons between TRW series for pines growing close together, i.e., at distances of about 60 m along transects T1 and T2, and more commonly in comparisons between pines of the transects spaced further apart, namely T3, T4, and T5. Moreover, no clear pattern of greater mutual similarity could be observed when considering

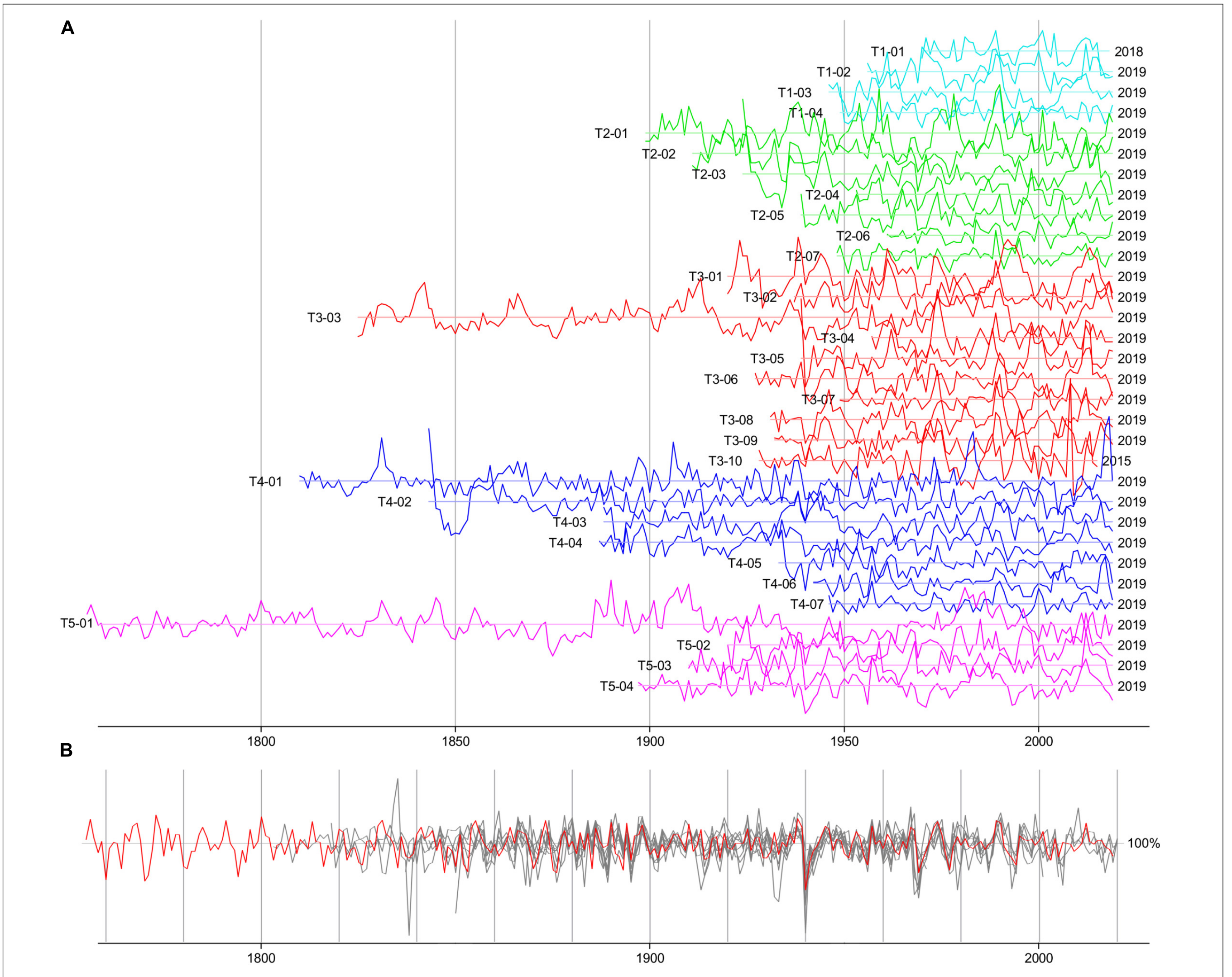

FIGURE 3 | Graphs of detrended TRW series for 32 pines along the five transects (T1–T5), in synchronous arrangement **(A)**. Graph of the chronology (red line) compiled from the TRW data for these pines, overlaid in synchronous arrangement on the graphs of absolute reference chronologies for pine (A–K) (semi-logarithmic scale; **B**).

only those pines growing on dune crests and those growing in the areas between the crests.

In contrast to the TRW series for individual trees, the chronologies ref. (A–K) compiled from these series did in most cases show a statistically significant degree of similarity (**Figures 3**, **4**). An exception is the chronology for the foot of Pūsēnu hill (B_2), compiled from the ring-width data of only three pines. This chronology showed a significant degree of similarity only with the pine chronology for the pines growing on the adjacent Pūsēnu hill (B_1) and with the chronology for the pines growing at Bernāti (A), fairly nearby (t-values of 6.4 and 6.6, respectively), whereas comparison with the other eight chronologies (C–K) gave low t-values [a t-value of 2.2 when compared with the Saka ref. chronology (D)]. Moreover, the chronologies for pines growing on sandy soils generally showed greater mutual similarity in those cases where the groups of pines they have been compiled from are located relatively nearby, but there were exceptions. For example, the Pūsēnu hill chronology (B_2) is less similar to the Saka ref. chronology (D), which relates to pines growing in somewhat nutrient-richer soils (t-value = 2.3), and to the Engure ref. chronology (H), on a site oriented in the opposite direction to the sea (t-value = 2.6). At the same time, the similarity between the Pūsēnu hill chronology (B_2) and the pine ref. chronology for the town of Ainaži (K), 265 km distant, is indicated by a t-value of 6.4. In interpreting these values, it needs to be borne in mind that they are affected by the quality and length of the chronologies.

More relevant to the initial aim of the study were results indicating the age of partially buried pines along coastline stretch 5. The core samples obtained from six of these had between 188 and 222 rings. The oldest rings in these cores fall in the period 1794–1806. Considering that the rings closest to the pith were missing from the core samples and that they had been taken relatively high up on the trunk (the root collar being buried quite deep in the sand), these pines began to grow at the same time, in the years before 1790. From this time onwards, young pines were no longer being buried in sand, which indicates that in this particular area dune formation had ceased for an extended period. The trunks of these pines were partially buried by sand later on, by which time they had grown sufficiently and were no longer under threat from sand accumulation.

These six pines, too, showed markedly diverging radial growth patterns. The most pronounced of the few pointer years appearing in the long TRW series for these trees is 1940, explicable in terms of the harsh winter conditions in the early part of that year (**Figure 5**).

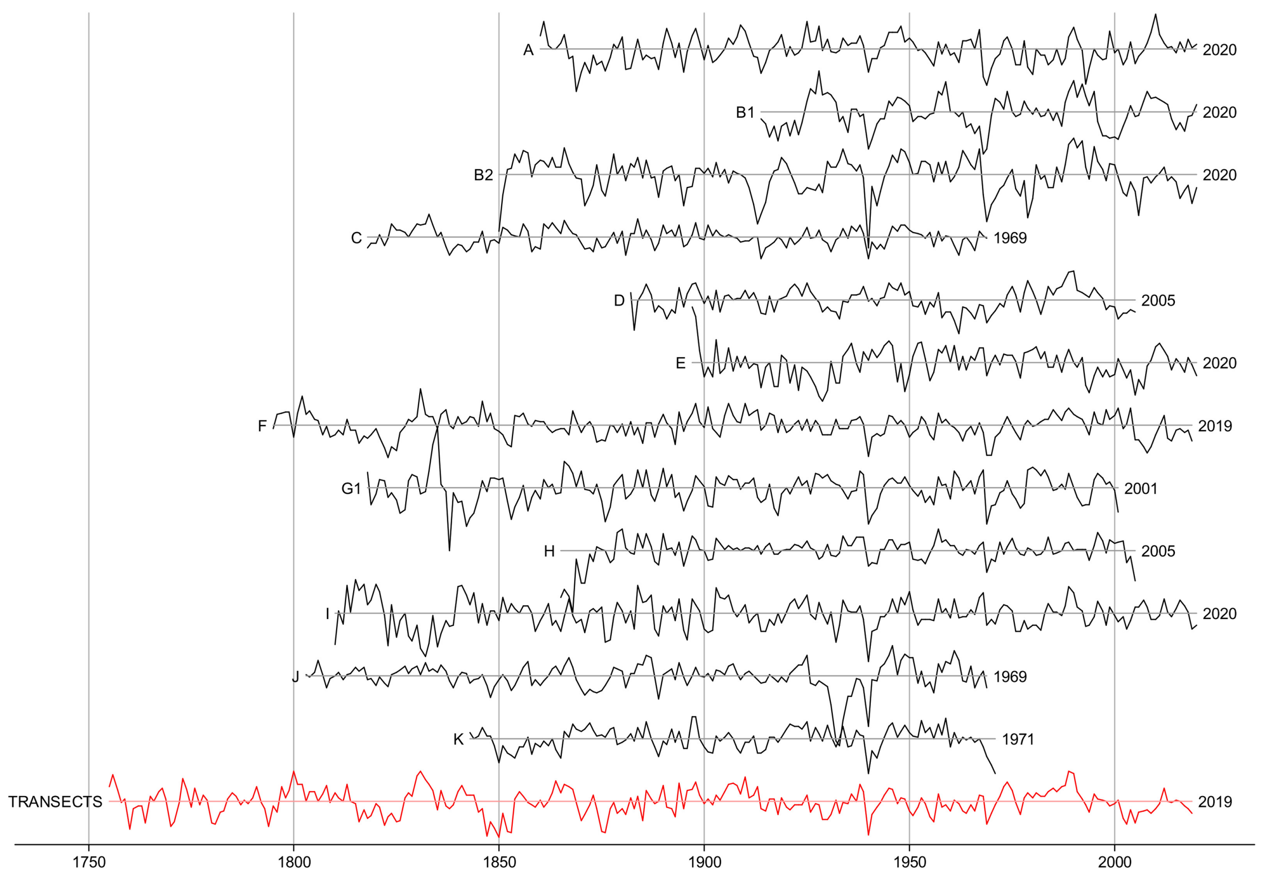

FIGURE 4 | Graph of chronology (red line) compiled from TRW series data of pines selected along the five transects and graphs of the absolute reference chronologies (A–K) in synchronous arrangement.

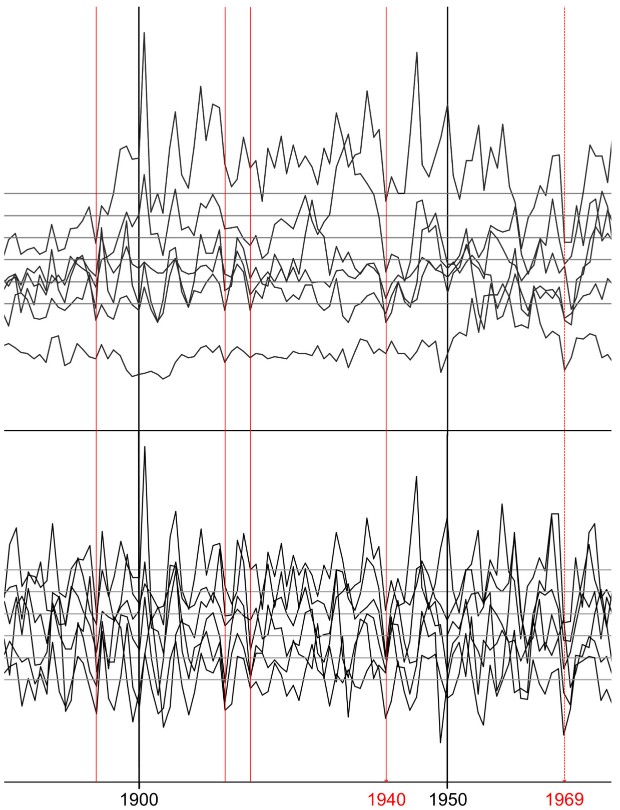

FIGURE 5 | The central section of the graph of TRW series for six pines of group 3 along coastline stretch 5 in synchronous arrangement: before data indexation (top) and after indexation (bottom). The most pronounced pointer year is 1940, when the winter was very harsh. The narrowing of ring widths in 1969–1970 corresponds very well to the time of two very strong autumn storms (1967 and 1969), in the course of which part of the coastal bluff was washed away.

Dendro-Dating of Ancient Trees

The 37 wood samples obtained from the apparently ancient pine trunk remnants and from some pines deeply buried by sand had between 30 and 280 tree rings, and in 21 cases the number of rings exceeded 80. The number of rings in most of the samples can be regarded as sufficient for dendro-dating; however, as mentioned above, dating of the apparently buried and re-exposed pine trunks proved to be problematic.

A statistically more significant degree of similarity (t-value > 5.0) with absolutely dated TRW series as well as with ref. chronologies was obtained for only three of the TRW series from apparently ancient pine trunk remnants. The date of the outer ring of one of the trunk remnants along coastline stretch 4 could be 1902, while that of another could be 1878. Considering the number of rings in these two wood samples (133 and 113, respectively), the two dates may, at first glance, be regarded as probable and credible, because this would mean that the two pines began to grow approximately at the same time: in the 1760s. However, there are also grounds for doubting the two dates: thus, soon after this date the landward migration of dunes along the coast of W Latvia began to occur on a previously unseen scale. Dune migration was successfully halted only after 1835, when dune stabilization measures, involving tree- and shrub-planting, were initiated (Bušs, 1960). Likewise, there is reason to doubt a third possible date (1704), obtained for the outer ring of a pine trunk remnant preserved on the upper slope of Pūsēnu hill, because the dune formed on its present site only 200–300 years ago (Janševskis, 1928).

The three ^{14}C-dated pines, represented by a trunk remnants in coastal stretch 5, most probably died in the period 1725–1785 (**Figure 6** and **Supplementary Table 1**: Liepene I-1, Liepene I-2, and Liepene I-4). The death of these trees may have been caused by the overly deep burial of its trunk in the course of dune migration. However, the calibrated ^{14}C date also indicates a quite high probability that the pine may have died in the 20th century. In this case, too, the TRW series of these trunk remnants did not show a significant degree of similarity to those of other sampled trees or to the chronologies.

Only the piles of a former jetty structure along stretch 4 have so far been dendro-dated. It has been established that the jetty was built of timber cut in about 1943, i.e., during the Second World War, although it is possible that the jetty is more recent, and was made from re-used timber. The TRW series for the jetty piles were relatively short (50–75 values), but the degree of similarity in synchronous position when compared against previously compiled pine ref. chronologies for Latvia was sufficiently significant (t-value: up to 5.7). The TRW series for the jetty piles showed a low degree of similarity with the TRW series for pines growing in the dune belt. It is highly probably that the jetty timber was sourced not from the coast but from an inland forest.

DISCUSSION: THE MAIN REASONS BEHIND THE PROBLEMS OF DENDROCHRONOLOGICAL DATING OF DUNE PINES

There is a basis for the hypothesis that the most frequent reason for the poor results of dendro-dating of apparently ancient pine stump remains could be the marked divergence in the radial growth pattern of tree trunks growing in earlier times, rather than an overly large difference in absolute age of the trunk remains. Although the time of death of trees buried by dune sands could have differed significantly along different stretches of the coast and at various distances from the coastline, a proportion of the trees within a relatively small area would most probably have died within a short period, or even simultaneously. In the case of trees growing simultaneously within a small area during a period up to the time of their death, the pattern of annual radial growth should, theoretically, have been rather similar, and so it should have been possible to synchronize the TRW series for these trees dendrochronologically. However, it has been found that the degree of similarity between the TRW series for such trees is too low, and this leads to the conclusion that in this particular

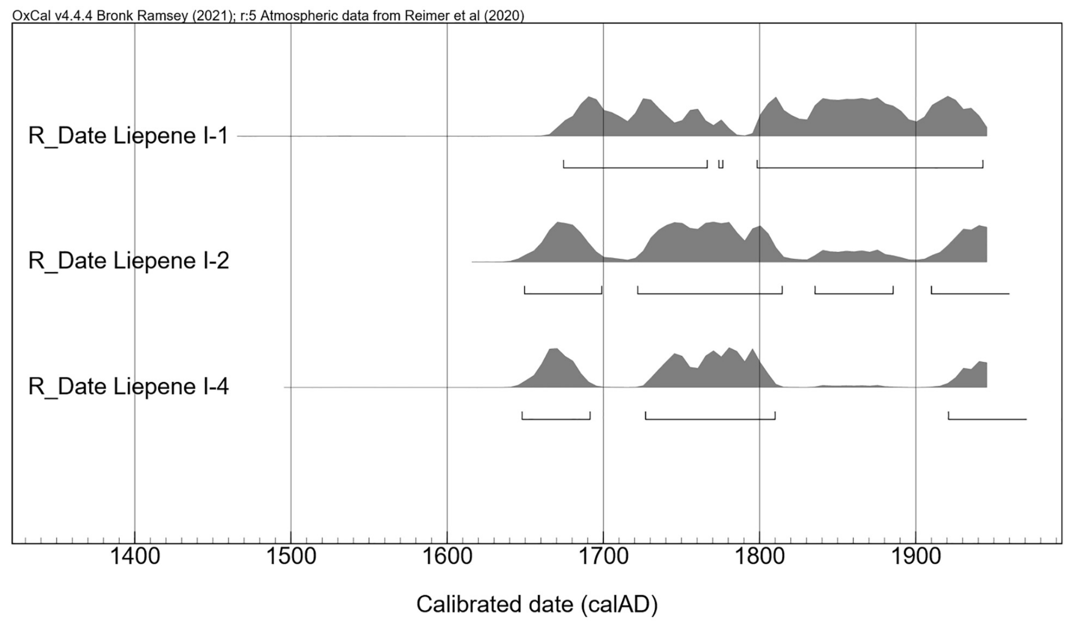

FIGURE 6 | Graph of calibrated dates of three ^{14}C-dated pine trunk remnants (coastal stretch 5, group 3).

case the main reason for the limited results of dendro-dating is the often markedly divergent growth pattern of pines in dune conditions.

In comparing the annual radial growth patterns of pines and considering the findings obtained in studies on this topic by other researchers, it was established that there could be several different causes for the differences in the growth pattern of pines growing in the coastal dune belt, which are sometimes very marked, and for the relatively poor results of the work to identify ancient trunk remains of pines by dendrochronology. These mainly relate to the characteristics of the environmental factors significantly affecting tree growth and their variation within the dune belt, and to the slope processes at the coastal bluff.

Differences in the Age of the Dunes

It was hypothesized from the outset that one of the reasons for the differences in the pattern of annual radial growth observed among pines growing in the dunes, seen most clearly among the 32 pines selected for study along the transects, is the difference in age of the dune formations traversed by the transects. There is a definite basis for such a view.

Once a pine trunk is buried by dune sand, the growing conditions for the tree change, also affecting the annual radial growth of the trunk. In a situation where dune formations migrate landwards in different periods, so that the pines growing in their path are partially buried by sand in different years, the impact on the trees' radial growth brought about by the changed growing conditions will not begin and proceed simultaneously and with equal intensity. Dune migration is a frequent cause of the death of pines; conversely, the cessation of dune formation or migration will eventually create favorable conditions for pine seedlings to grow. Thus, the age of the dunes may affect the age of pines growing even relatively close to one another, as well as the character, timing and duration of the impact of the significant altered environmental conditions on the growth of older pines.

It should be added that not only N of Ventspils (located at the mouth of the River Venta) but also in the environs of Cape Kolka, such dune formations differing in age could actually be quite old. Along these stretches of the coast, intensive erosion is continuing, so that the sea is currently eroding coastal areas with relief consisting of dunes that have migrated relatively far inland in earlier periods. It has been established that over a 100-year period the coast at Cape Kolka has retreated by 350 m, while the coast N of Ventspils has retreated by 100–180 m (Eberhards, 2003).

Specific Climatic and Edaphic Factors

Another very important reason for the for the lack of statistically unequivocal dendro-dating results is to be found in the somewhat specific environmental factors operating in the coastal dune belt. This includes climatic as well as edaphic factors. Climatic factors (mainly air temperature and precipitation) are generally the main interannually varying factors which, since they affect tree growth across relatively large areas, permit the cross-dating of the TRW series characterizing the growth of these trees (Speer, 2010). In Latvia, the radial growth of pine in mineral soils with a moderate soil moisture level is most significantly affected by mean air temperature during the last months of winter and the first months of spring, i.e., from January or February up to mid April (Elferts, 2007; Zunde et al., 2008). It has been established in two studies that the local air temperature in the mentioned period also correlates positively with the radial growth of pine growing at the present day

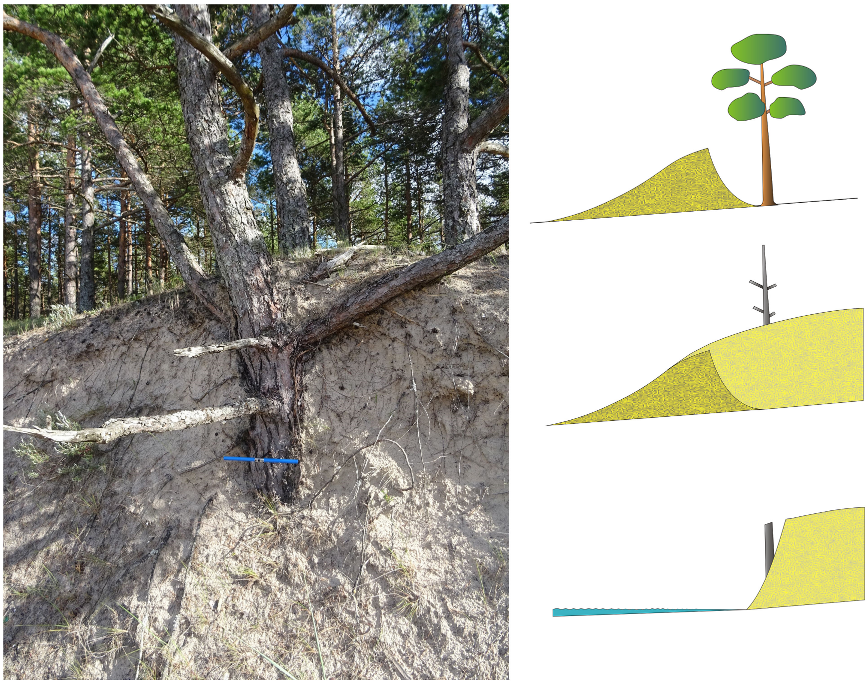

FIGURE 7 | Trunk of a surviving pine partially re-exposed at the coast between Mazirbe and Kolka (stretch 6) as a result of coastal bluff erosion after burial by sand (photograph). Burial of the lower part of a pine trunk and subsequent re-exposure of its stump (scheme).

on sandy coastal sites (Elferts, 2007; Matisons and Brūmelis, 2008). However, it should be added that this relationship has been observed and confirmed only using ring-width data for pines exhibiting a fairly similar pattern of annual radial growth (Elferts, 2007; Matisons and Brūmelis, 2008). These two publications do not address the question of why the remaining trees, 26 and 43%, respectively, of the trees included in the studies showed a different or even individual pattern of annual radial growth variation. In contrast to dendroclimatic studies that utilize present-day tree-ring data, when dating samples of historical wood from various sites, the dendrochronologist does not have the possibility of making such a selection, because the task is to establish the absolute age of all the wood samples under study.

At the Baltic Sea coast, especially along Latvia's west coast, which has a maritime climate, winter and spring air temperature is not such a significant factor for the radial growth of pine as it is in the eastern part of the country. Along Latvia's western seaboard, in the period 1950–2003, the mean January temperature was −1.9 to −2.4°C, whereas in the eastern part of the country it was as low as −6.2 to −6.7°C (Kļaviņš et al., 2008). Correspondingly, in the period 1945–2004, SW Latvia had a mean snow cover duration of 66–77 days, whereas in the NE of the country snow cover lasted almost twice as long: a mean 123–134 days (Draveniece et al., 2007). Since the air temperature in winter and spring in the coastal areas is relatively higher and subject to smaller fluctuations than in areas further inland, the impact on the radial growth of pine is reduced. This is even more so in the current period of global warming. The different pattern of radial growth of the pine trunks under study testifies that interannual variation is more frequently determined not by low air temperature but by other environmental factors having a local or even individual character. At the seacoast, these could include soil moisture, relief (aspect) and associated soil warming, as well as the level of solar insolation, the burial of tree trunks by sand, or the converse, namely erosion, and other factors. Other observations have confirmed the absence of a statistically significant correlation specifically between the radial growth of pines growing on dune summits and interannual variation in monthly mean air temperature (Mandre et al., 2010).

In the dunes along the Baltic Sea shore the influence of the precipitation level on tree growth likewise tends to have a highly localized character. In an area with a similar level of precipitation, the moisture content of sand on dune summits differs from that of hollows. It has been found that soil moisture at a depth of c. 20 cm may differ as much as six times between dune summits and hollows (Mandre et al., 2010). This difference is not due solely to water drainage from the dune summits to the hollows and increased evaporation at the summits because of greater exposure to the sun and wind. A greater amount of fine wind-borne sand accumulates on the dune summit and on the windward slope, whereas coarser, heavier sand that the wind cannot set in motion so rapidly and for such a great distance will be deposited in greater amounts in the dune hollows. Water permeates the coarse sand more quickly, reaching a greater depth, and the capillary rise height is relatively low. If the depth of permeation of precipitation is close to or even reaches the groundwater level, then anaerobic

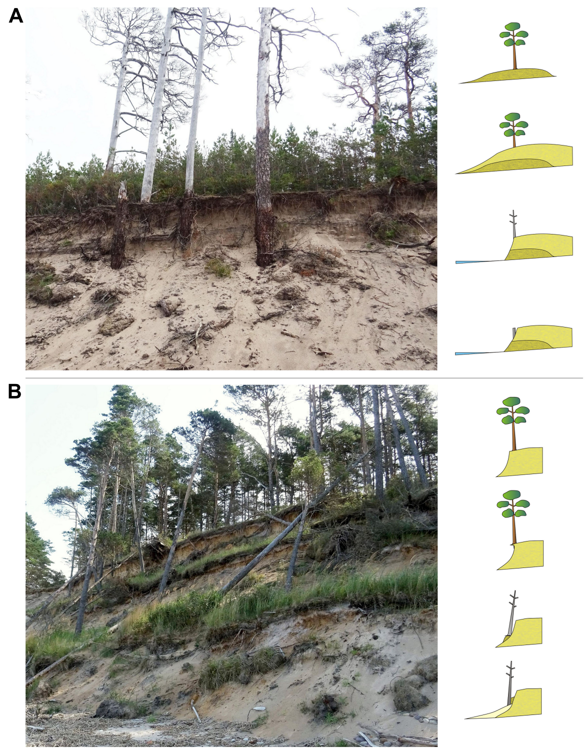

FIGURE 8 | (A) Re-exposure of pine trunks on the face of the coastal bluff long after burial (photograph from Liepene, stretch 5, tree group 3; scheme). **(B)** The face of the coastal bluff with pines remaining in vertical condition, having partially slumped down the face along with the soil (photograph from Staldzene, stretch 4, not sampled; scheme).

conditions can develop in the sand in the corresponding time period, which is unfavorable for tree growth (Bušs, 1960).

The trees growing on dune summits, whose roots are generally better oxygenated, tend to suffer from nitrogen deficiency. Nitrogen is absent from the mineral component of the sand, being present only in the organic remains in the sand, which accumulate in greater amounts in the dune hollows (Bušs, 1960).

Thus, even in seemingly uniform dune sands the growing conditions for trees may differ markedly. The growing conditions vary even more markedly in the case of pines whose trunks are partially buried by sand. It has been established that pines that have been deeply buried by sand react less strongly to marked temperature changes, and accordingly it is in some cases quite difficult to cross-date their TRW series (Vitas, 2004; Matisons and Brūmelis, 2008; Mandre et al., 2010).

Problem Factors in the Cross-Dating Tree-Ring Width Series

Most of the core samples from pine trunk remnants proved unsuitable for dendro-dating. In many cases the wood was at least partly decayed, and in some samples the wood was very resinous or showed very dense galleries created by wood-boring insects. The sawn samples revealed that in some samples the ring width varies considerably between different parts of the trunk circumference, and in such a case the ring widths, as measured on a core sample only about 5 mm in diameter, may give a very erroneous indication of the mean annual radial growth around the circumference of the trunk in any given year.

When tree ring width measurements were obtained from the sawn samples, it was found that several of these lack the outer part of the wood, so that a considerable number of rings have been lost. Because of decay of the outer part of the trunk and abrasion by wind-blown sand, the sapwood as well as the outer part of the heartwood was missing around almost the whole circumference of the trunk remnants. It appears very likely that burial of the lower part of the pine trunk by a thick layer of sand is the reason for a drastic reduction in annual radial growth at least in the case of some of these pines. For example, on one of the sawn samples the wood of the outer part of the trunk was preserved in a very narrow sector. Here, 80 rings were present in a thickness of about 1 cm. In such a case, where the radial growth in this direction was only a mean 1 mm in 8 years, there is a very high probability that one or more rings are missing. In any case, such thin tree rings provide only a very weak and imprecise reflection of the climatic signal.

The missing rings, i.e., the absence of the rings in the wood samples often further exacerbate the problem of cross-dating of TRW series of deeply buried pines (Vitas, 2004; Matisons and Brūmelis, 2008). It is concluded that missing rings are more frequent in pines growing on dune summits, because the annual rings of these pines are generally narrower due to the unfavorable growing conditions (Mandre et al., 2010). It should be added that due to the effect of prevailing onshore winds, predominantly one-sided exposure to light and the stresses caused by one-sided burial under sand, the radial growth of pines growing at the seacoast is commonly asymmetrical. Under the conditions of lateral pressure, reaction (compression) wood will be formed on the opposite side of the trunks of coniferous trees, with widened rings that generally give a poorer reflection of the dendrochronological signal (Janecka et al., 2016). Reaction wood was observed in several of the sawn samples.

Many of the pines that had died recently were affected by wood degradation under the bark, while the trunk remnants were also in many cases rotten inside. Accordingly, for precise dating of ancient pine trunks it is important to try to obtain sawn slices instead of drilled (core) samples, since the quality of the latter may be markedly impaired for the above-mentioned reasons. Sawn slices permit easier identification of missing rings, as well as improving the general quality of the dendrochronological signal, as reflected in the TRW series.

The cross-dating of TRW series from the presumed ancient pine trunk remnants was also complicated by the absence of reliable indicators that several trunk remnants could be of equivalent age. In contrast to the wall of a log structure, for example, where the timbers are very likely to have been made from trees cut the same year, and accordingly the relative date of each successive timber is to some degree predictable, it was difficult or even impossible to assess in

FIGURE 9 | Pines growing on the face of the coastal bluff at the coast between Mazirbe and Kolka (stretch 6, not sampled), where erosion has ceased for an extended period. All photographs by the author.

advance the chronological relationship between pine trunk remnants identified separately and at different levels on the coastal bluff, especially since in some cases part of the sapwood layer had been abraded by the action of wind-blown sand. Because of the greater differences in date among the ancient tree trunks, there is an increased risk of subjective error when comparing the (generally short) TRW series and seeking to identify which of several possible datings is the true one. And when determining the relative date of just a small number of wood samples, it is harder to maintain the principle of replication, so important in dendrochronology (Fritts, 1976; Speer, 2010).

Coastal Erosion Processes Active at the Present Day

The initially prevailing view was that the trunk remnants seen in certain places on the face of the coastal bluff most probably represent the upper parts of the lower sections of pine trunks preserved under the cover of sand, in at least partially anaerobic conditions, and exposed on the face of the bluff by erosion (**Figure 7**). Remains of tree trunks buried by sand in this way and subsequently exposed could be from very ancient trees. However, it was noted in the course of the survey of the coastal stretches that the lower part of the trunk of a pine that has died fairly recently may actually resemble the trunk remnant of an ancient tree, and indeed such a remnant of a recent pine can end up on the face of the coastal bluff or be exposed here in at least three different ways.

Self-sown and planted pines on lower coastal dunes, for example on former foredunes, may, once they have grown, be partially buried by one or more additional layers of sand. Under such conditions, some of the partially buried pines may die, and the above-ground parts of the trunk may decay, whereas the lower part of the trunk, covered and preserved by relatively younger sand layers, may subsequently be exposed on the partially eroded face of the coastal bluff (**Figure 8A**).

It was observed at some sites that partial erosion of the coastal bluff had been followed by a time interval during which the sand forming the bluff had repeatedly collapsed due to the effect of desiccation and wind action, and partly also due to precipitation and the weight of ice. This had also been followed from time to time by the slumping by various amounts of the undercut soil, along with the trees rooted in this soil. In several cases the pine trunk had retained its vertical position after slumping (**Figure 8B**), and as erosion continued the trunks of some trees, initially resting against the face of the bluff after the slump, had been pushed back into a vertical position by the weight of the slumped soil and sand. Continued erosion of the coastal bluff, along with a further supply of sand from the seaward side, increasingly buried the lower section of the slumped tree trunk. The remains of such stumps, once re-exposed, may likewise be reminiscent of the trunk remnants of trees buried by sand in ancient times. Moreover, a soil surface that has slumped from the top of the coastal bluff along with the trees rooted in it may in some cases be mistaken for a former soil surface at this level that has been covered by a thick layer of sand.

It is also necessary to mention the trunks of living as well as dead pines of relatively recent origin observed on stretches of the face of the coastal bluff that have not been impacted by coastal geological processes for an extended period of time.

Along such stretches of the coastal bluff, regeneration not only of the herb layer but also of pines is sometimes seen. Having grown larger, some of these pines have died because of the rather unfavorable conditions, but in contrast to the above-described examples, the trunk has generally been preserved in its full length (**Figure 9**).

The date of death of pines growing on the face of the coastal bluff or very close to it may differ considerably, and thus may not indicate the actual date when the particular stretch of the bluff was eroded. Pine trees may die prematurely when the bluff retreats almost up to the site where they have been growing, whereby moisture from precipitation along with dissolved nutrients is no longer retained in the soil but is instead drained away to the face of the bluff. This promotes desiccation and subsequent collapse of the topsoil, as well as the death of the trees, because of the reduced soil moisture as well as the exposure of roots on the bluff face.

CONCLUSION

The study revealed the complexity and difficulties of dendro-dating individual trunk remnants of pines that have grown in dunes. Compared with pines growing in inland areas, the annual radial growth of pines in the coastal dune belt is relatively less affected by any particular large-scale climatic factor, whereas local as well as individual environmental factors have a proportionally greater impact. Accordingly, the pattern of year-to-year variation in annual radial growth is more idiosyncratic. However, it is concluded that the tree-ring chronologies compiled from mean TRW series data for successfully cross-dated pines growing in a small area can be synchronized with other chronologies. This gives grounds for the hope that, once a major concentration of ancient pine trunk remnants is discovered in the dune belt (i.e., corresponding to a former forest tract), dendro-dating could be much more productive. Trunk remains from biologically old trees offer a better chance of obtaining a relative as well as an absolute dendro-date. Additionally, it would be useful to initially obtain approximate dates for a number of apparently ancient trees by ^{14}C dating.

The realization that the annual radial growth pattern of dune pines is rather heterogeneous permits the conclusion that, for example, the dendro-dating of local timber used for wooden buildings in Riga in the 13th and 14th century has in many cases proceeded with more difficulty, when compared with the dating of timber floated down the River Daugava, such as was more commonly used for Riga buildings in later times, not only because of the greater variation in soil conditions in the environs of Riga, and because the later floated timber was coming from forests growing in more continental climatic conditions (Zunde, 2020), but also because the local timber was being sourced also from the dunes near Riga, where the radial growth pattern of the pines was more idiosyncratic.

Observations along the surveyed stretches of the coast as well as the dendro-dates of pines partly exposed on the coastal bluff face and of some exposed trunk remnants show that the majority of pine trunk remnants discovered in the course of survey are not hundreds but, at most, a couple of decades old. Several badly degraded trunk remnants, generally of small diameter, might be from an earlier period, but these were not sampled because of the poor preservation and the small numbers of annual rings. Some tree stumps discovered on the beach itself, only up to about 1 m above the sea level and only visible briefly, sometimes with only the top of the stump exposed, could likewise be earlier in date. The lower-lying ones were soon covered with a new layer of beach sand, suggesting the possibility that there might be a greater number of tree stumps deeper in the moist sand. Such finds could potentially be investigated in future research.

Knowledge of the age of long-lived trees growing in dune conditions at the present day could provide important insights into the history of dune migration. At least in the case of the Latvian coastal belt, pines 250 years and older can indicate the approximate date when dune migration ceased in a specific area.

To what extent the pattern of tree-ring width variation can be used to characterize the timing and degree of burial of a tree trunk in sand and its subsequent re-exposure–this remains a question for future in-depth study. However, as shown in this study and in previous research, the development of pines growing in dunes is affected by several important, relatively pronounced and in many cases unstable local environmental factors. Significant changes in the radial growth rate during the life of a pine tree were identified only in the case of a small number of trees, and moreover these do not relate to the same chronological interval. Accordingly, a causal link with changes in the level of the sand partially burying the tree trunk could not be demonstrated. It is concluded that, in order to answer these questions, further research should also seek to obtain a clearer understanding of how environmental factors other than burial by sand affect the growth of dune pines.

Since it has been established that the degree of similarity between tree-ring chronologies for pines growing in the coastal dune belt and in inland areas of Latvia is sufficient to permit them to be synchronized, it transpires that future attempts at absolute dating of potentially ancient pine trunk remnants should make use of a larger sets of tree-ring data from this kind of material. Ancient pine trunk remnants along the coastal bluff providing wood samples of sufficiently good quality for dendro-dating generally occur only in relatively small numbers. Accordingly, better success could be expected if, instead of seeking to relatively date trunk remnants exposed at any one time along a fairly long stretch of the coast, dating were to be undertaken on trunk remnants that are exposed in the course of a number of years along shorter stretches of the coast, as the coastal bluff retreats. There is reason to believe that the pattern of annual variation in ring-width of pines growing at approximately the same level, which are progressively exposed during an extended period, should exhibit a higher degree of similarity. In this way, relative chronologies might be compiled for pines growing in stands covering fairly small areas, and this would considerably increase the chances of synchronization with relative chronologies for other small-scale pine stands in the dunes as well as with absolute chronologies for pines relating to nearby inland areas.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2022.734030/full#supplementary-material

Supplementary Figure 1 | TRW series and absolute tree-ring chronologies for living pines utilized in the study. **(A)** TRW series for living and recently dead pines. **(B)** TRW series for pine timbers from jetty structure. **(C)** TRW series for pine trunk remnants. **(D)** Absolute tree-ring chronologies for living pines. [a]Undated pine TRW series (not in synchronous arrangement). [b]Relatively dated pine TRW series. [c]Previously compiled absolute tree-ring chronologies for pine. [d]Absolute tree-ring chronologies for pine compiled in the course of the study. [e]Number of TRW series used to compile chronology. [f]Numbers of investigated coastal stretches/sites.

Supplementary Table 1 | Previously and newly obtained ^{14}C datings utilized in the study.

Supplementary Table 2 | *T*-values indicating the degree of similarity between the tree-ring series of pines selected along the transects, extracted from the overall matrix. The empty cells indicate cases where the similarity of the pairs of TRW series in synchronous position shows a *t*-value which is not among the five highest *t*-values for the similarity between the two TRW series (i.e., the five highest *t*-values are fortuitous).

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