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THE EFFECTS OF A SEA LEVEL RISE ON THE ESTONIAN COASTLINE

Introduction

It is now widely accepted that the increasing concentrations of carbon dioxide and other gases generated by human activities in the Earth's atmosphere, measured in recent decades, will continue, and will lead to global atmospheric warming: the so-called Greenhouse Effect. This, in turn, will result in thermal expansion of the oceans, and the partial melting of glaciers and ice sheets, which will add to the volume of water in the oceans, producing a world-wide rise of sea level (Barth, Titus, 1984; Bird, Koike, 1986). Hoffman (1984) estimated that global sea level will rise 0.24 to 1.17 metres by the year 2050, and 0.56 to 3.45 metres by the year 2100. According to these predictions, global sea level will stand one metre higher than it is now by the year 2045 (high scenario), or the year 2140 (conservative scenario) (Fig. 1).

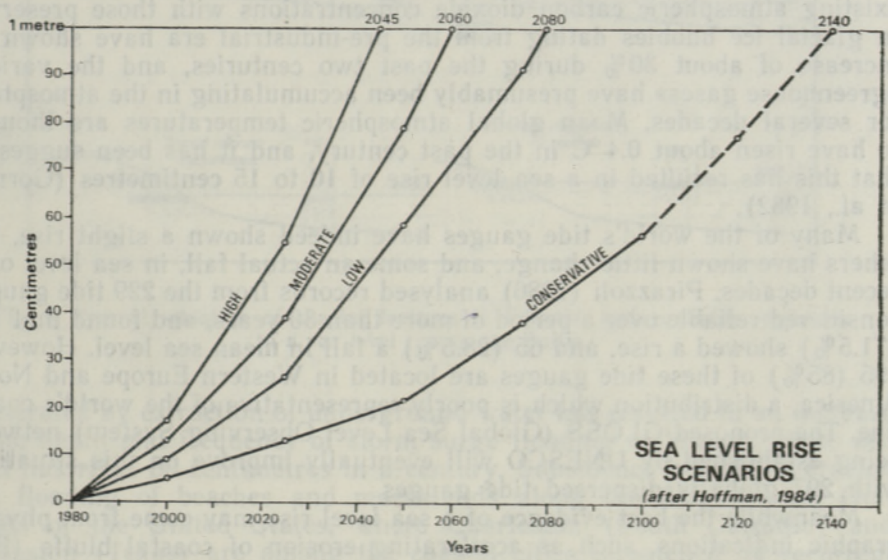

Fig. 1. Predictions of global sea level rise as a consequence of the Greenhouse Effect.

Factors that complicate the prediction of actual changes on various parts of the world's coastline include tectonic uplift or subsidence of the land margin, the effects of the additional water load, which may hydro-isostatically depress the submerging land and thus augment a sea level rise, and the spatial variability of ocean surface levels, which make it unlikely that the rise of sea level will be equivalent around the world's coastline, even on sectors where the land margin remains stable (Mörner, 1985; Pirazzoli, 1985).

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In the Baltic region, tectonic movements resulting from isostatic recovery following deglaciation of the Scandinavian region continue to raise the land in Finland and northern Estonia, whereas southern Estonia and the south coasts of the Baltic Sea are subsiding. A global sea level rise of one metre in a century will thus be offset by the continuing tectonic uplift of northern Finland: in the Oulu region, where the land is rising about a centrimetre per year, there would be no apparent change of sea level after a century. In southern Finland and northern Estonia the global sea level rise of one metre would be reduced by tectonic uplift of several centimetres, whereas in southern Estonia the relative rise of sea level in the Gulf of Pärnu would exceed one metre.

As a first approximation, the effects of a one metre global sea level rise on the Estonian coastline during the coming century may be estimated by adding or deducting the tectonic component, and then surveying the contour at the resulting level above present high water line. Allowance must be made for erosion or deposition as submergence proceeds. Coasts backed by soft materials, such as dunes or glacial drift, would be cut back by erosion as sea level rose, whereas deposition around the mouth of a major sediment-yielding river could offset some of the submergence produced by a rising sea level, or even maintain progradation.

Is global sea level rising?

There is some uncertainty over whether the Greenhouse Effect has already produced global warming and sea level rise. Comparisons of existing atmospheric carbon dioxide concentrations with those preserved in glacial ice bubbles dating from the pre-industrial era have shown an increase of about 30% during the past two centuries, and the various «greenhouse gases» have presumably been accumulating in the atmosphere for several decades. Mean global atmospheric temperatures are thought to have risen about 0.4 °C in the past century, and it has been suggested that this has resulted in a sea level rise of 10 to 15 centimetres (Gornitz et al., 1982).

Many of the world's tide gauges have indeed shown a slight rise, but others have shown little change, and some an actual fall, in sea level over recent decades. Pirazzoli (1986) analysed records from the 229 tide gauges considered reliable over a period of more than 30 years, and found that 162 (71.5%) showed a rise, and 65 (28.5%) a fall in mean sea level. However, 195 (85%) of these tide gauges are located in Western Europe and North America, a distribution which is poorly representative of the world's coastline. The proposed GLOSS (Global Sea Level Observing System) network being established by UNESCO will eventually improve on this situation, with 297 globally dispersed tide gauges.

Meanwhile the best evidence of a sea level rise may come from physiographic indications, such as accelerating erosion of coastal bluffs (Fig. 2A) and beaches (Fig. 2B), the enlargement and deepening of coastal lagoons and estuaries (Fig. 2C), retrogression of coastal vegetation, particularly on salt marshes (Fig. 2D), and the landward and upward migrations of zoned organisms on cliffs and rocky shores, and on structures such as sea walls and pier supports (Fig. 2E) (Bird, 1988).

The effects of a rising sea level are already evident on those parts of the world's coastline that are subsiding tectonically, and have thus had an effective sea level rise in recent decades. These include the Netherlands, where the land is subsiding at up to 20 centimetres per century, and the south and east coasts of England, where successively higher storm surges have necessitated the building of barrages in the Thames estuary to prevent the flooding of parts of London. In north-eastern Italy, subsidence

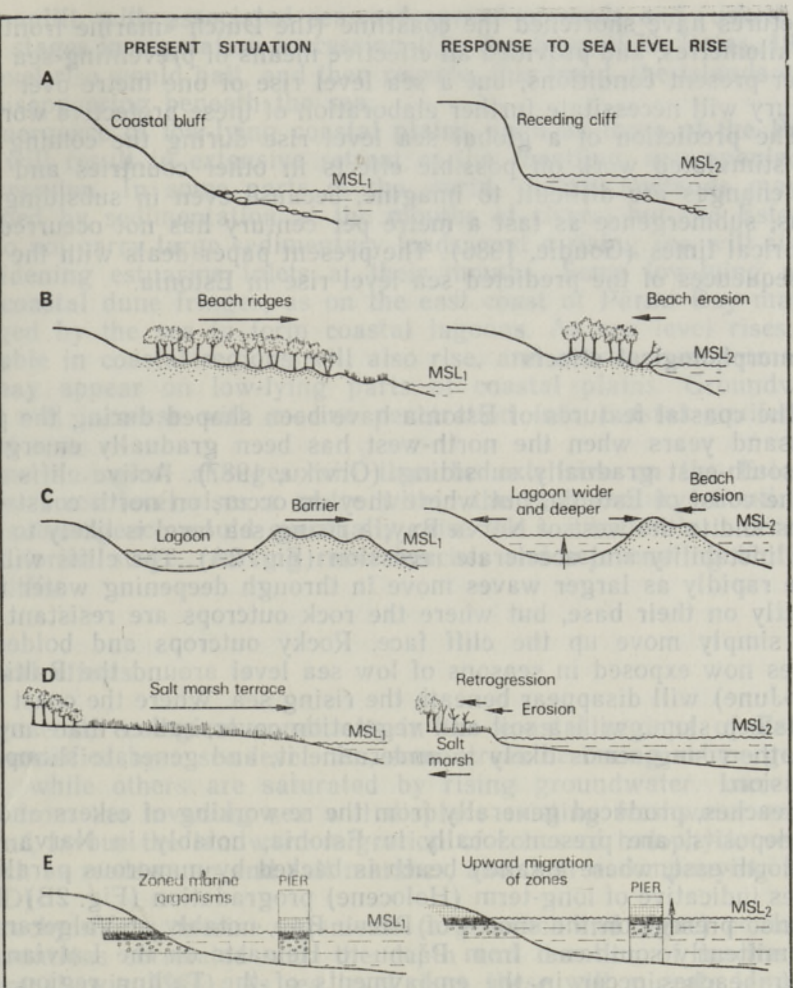

Fig. 2. Present situation of coastal features in Estonia, and probable responses to a sea level rise in the Baltic.

accelerated by extraction of underground water has resulted in an increase in the depth and frequency of storm surge flooding of Venice, where sea level has risen 30 centimetres in a century. Subsidence has led to erosion and flooding of beaches and marshlands along the Atlantic and Gulf coasts of the United States, where Charleston (South Carolina) and Galveston (Texas) are among the coastal cities threatened by recurrent sea flooding. Other areas where coastal subsidence has resulted in recurrent flooding and the need for sea dykes to protect low-lying areas and pumping schemes to dispose of surplus water include Bangkok in Thailand, Taipeh in Taiwan, Tokyo and Niigaata in Japan, and the deltaic north coast of Java, east of Jakarta.

Experience gained in these areas is likely to prove valuable as the global sea level rise spreads and accelerates. In the Netherlands, where one third of the country is already below sea level, storm surge flooding from the North Sea in 1953 prompted the rebuilding of coastal dykes. The Dutch Delta Project, with construction of barriers and artificial islands to control water flow at the mouths of the Rhine, the Maas, and the Scheldt Rivers was completed in 1986 at a cost of $US2,000 million. These structures have shortened the coastline (the Dutch «marine frontier») by 688 kilometres, and provided an effective means of preventing sea flooding under present conditions, but a sea level rise of one metre over the next century will necessitate further elaboration of these protective works.

The prediction of a global sea level rise during the coming century has stimulated work on possible effects in other countries and regions. The changes are difficult to imagine, because even in subsiding coastal areas, submergence as fast a metre per century has not occurred during historical times (Goudie, 1986). The present paper deals with the possible consequences of the predicted sea level rise in Estonia.

Geomorphological effects

The coastal features of Estonia have been shaped during the past few thousand years when the north-west has been gradually emerging and the south-east gradually subsiding (Orviku, 1987). Active cliffs are rare on the coast of Estonia, but where they do occur, on north coast promontories and to the west of Narva Bay, a rising sea level is likely to promote their instability and accelerate recession (Fig. 2A). The cliffs will retreat more rapidly as larger waves move in through deepening water to break directly on their base, but where the rock outcrops are resistant the sea will simply move up the cliff face. Rocky outcrops and bolder-strewn shores now exposed in seasons of low sea level around the Baltic (as in May-June) will disappear beneath the rising sea. Where the coast consists of a steep slope, with a soil and vegetation cover, rather than an eroding cliff, the rising sea is likely to undermine it, and generate slumping and recession.

Beaches, produced generally from the re-working of eskers and morainic deposits, are present locally in Estonia, notably in Narva Bay, in the north-east, where a sandy beach is backed by numerous parallel dune ridges indicative of long-term (Holocene) progradation (Fig. 2B). Beaches are also present on the shores of Pärnu Bay, notably at Valgeranna, and intermittently south-east from Pärnu to Heinaste on the Latvian border. Minor beaches occur in the embayments of the Tallinn region, and on the islands of north-west Estonia.

A sea level rise is likely to lead to submergence and erosion of these beaches. Most of them will disappear beneath the sea, but where they are backed by extensive dunes (as in Narva Bay) they will persist at higher levels as sea level rises and the coast retreats. Where the rising sea encounters older beach deposits, such as the beach and dune sands of the Litorina Sea and Ancylus Lake stages, which occur a short distance inland from the coast south-east of Pärnu, beaches will revive at higher levels.

Erosion is already extensive on the world's beach-fringed coasts, recent studies having shown that beaches are prograding only where there is a continuing supply of sediment (e. g. from nearby rivers, melting glaciers, spilling dunes or eroding cliffs, or washed in from the sea floor), or where beach material drifting alongshore is being trapped alongside breakwaters (Bird, 1985). Beach erosion is the result of a number of factors (the Table), and cannot be taken as an indication of sea level rise, although it has been contributory (factor 9 in the Table) on coastlines that are subsiding tectonically, as on the Atlantic seaboard of the United States.

As submergence proceeds, coastal inlets, embayments, and estuaries will enlarge and deepen (Fig. 2C) as their reedswamp and salt marsh islands and fringes are submerged, and salinity penetration into them will increase. In the Matsalu Bay region of north-western Estonia nearshore shoals have been emerging, and islands enlarging as the result of tectonic uplift, with associated seaward spread of reeds and rushes, and ensuing stages in vegetation succession (Orviku, Sepp 1972; Ratas, 1988). A sea level rise would halt, and then reverse, this trend, the islands eventually disappearing beneath the sea.

Submergence of low-lying coastal plains, such as those of the Pärnu region, will result in extensive retreat of the coastline, accompanied by marine erosion. In some parts of the world, deltaic lowlands may be maintained by sedimentation at the mouths of rivers, but the Estonian rivers do not carry large sedimentary loads, and a rising sea will simply form widening estuarine inlets at their mouths. Some low-lying areas behind coastal dune fringes, as on the east coast of Pärnu Bay may be submerged by the sea to form coastal lagoons. As sea level rises, the water table in coastal regions will also rise, and seasonal or permanent lakes may appear on low-lying parts of coastal plains. Groundwater salinity will increase with marine penetration into coastal aquifers as sea level rises.

Geomorphological changes will thus be extensive on the Estonian coastline if sea level rises a metre within the next century. Continuing marine submergence would eventually raise the sea to levels it occupied at the Litorina stage, reviving relict beaches and rejuvenating bluffs as active cliffs.

Ecological effects

In general, ecological conditions in the coastal regions of Estonia will be modified by a sea level rise, some areas becoming submerged by the sea, while others are saturated by rising groundwater. Increasing salinity from the invading sea will displace existing freshwater ecosystems, and favour the landward migration of zones of halophytic vegetation, such as reedswamp and salt marshes, and their accompanying fauna (Fig. 2D).

On rocky shores, marine organisms (e. g. wrack and algae) commonly show zonations correlated with the depth and duration of marine submergence (Lewis, 1964). As sea level rises, these will migrate landward across rocky shores and upward on cliff faces, stacks, and rocky protrusions. Similar upward movements may be expected where artificial structures such as sea walls, groynes, breakwaters and pier supports have zoned encrustations of marine organisms (Fig. 2E).

Low-lying coastal wetlands will also show migrations of vegetation and faunal zones as submergence proceeds. On parts of the Estonian coast there has been progradation, accompanied by the seaward spread of reedswamp or salt marshes during Holocene times, especially in the emerging sectors of the north and north-west. Associated deposition of sediment, together with peat accumulation, has formed marshland terraces in environments such as the fringes of Matsalu Bay. A sea level rise will impede, halt, and reverse this sequence, unless sedimentation continues (or is artificially supplied) at a sufficient rate to maintain the depositional terrace by vertical accretion and hold, prograde, or protect the coastline (Redfield, 1972). Otherwise, submergence will kill the seaward reedswamp and salt marsh communities, and initiate erosion of the previously prograded marshland terrace. If sedimentation is sufficient to maintain vertical accretion the existing vegetation patterns will persist (Pethick, 1981), but where the marshland remains at its present level during a sea level rise, retreat of the coastline will be accompanied by landward migration of the salt marsh communities into the hinterland. As salt marsh communities regenerate quickly in areas that have been cleared, then abandoned, it is likely that they will spread back on to suitable low-lying hinterlands as the sea rises, but where the hinterland is steep or rugged, or where such landward spread is prevented by artificial embankments or developed land, these halophytic zones will be narrowed and extinguished as marine submergence proceeds.

Ecosystems of coastal regions will thus change as sea level rises, but on much of the Estonian coast the natural vegetation and fauna has already been extensively modified, and what actually happens will depend very much on human responses to ecological change.

Human responses to coastal submergence

The ways in which modern coastal societies will respond to a relatively rapid global rise in sea level will vary with political and economic factors. Nations that have the organisation, technology, and resources to counter the effects of a sea level rise by means of artificial structures will do so, on the model of the Netherlands; others will in general have to choose between evacuation of submerging areas or adaptation to changing coastal environments. An example of this has been observed on the north coast of New Guinea, where the narrow sandy barrier enclosing the Murik Lakes, on the shores of the Sepik delta, has been repeatedly overwashed by storm surges and driven landward. Native villages established on this barrier have been moved back and rebuilt after each storm surge (Bird, 1987).

On coastlines close to urban and industrial centres it is likely that a sea level rise of about a metre over the next century will stimulate expenditure on structures designed to prevent submergence and erosion. This is already the case in the Thames estuary, and on the Dutch Delta coast, and similar protective measures are planned to save the city of Venice from submergence and destruction by increasingly high storm tides (Pirazzoli, 1983). It is very likely that where land has recently been reclaimed from the sea for use by large coastal populations (as in Singapore, Hong Kong, and Tokyo Bay), strenuous efforts will be made to retain it by building sea walls and introducing pumping systems, using techniques familiar from the history of the Netherlands coast. Where waste water disposal systems presently use outfall by gravity they may have to be redesigned, perhaps to incorporate pumping devices, if they are to remain serviceable as sea level rises. Few existing artificial structures have been designed to cope with the effects of a one metre sea level rise. At Galveston, for example, the existing oceanside sea wall will be overtopped and outflanked by larger storm surges after a metre sea level rise, and extensive supplementary works will be necessary (Leatherman, 1984).

Beaches that are valued for recreation or tourism, as in seaside resorts, may be maintained by beach renourishment programmes of the kind already used in the United States and Australia. More generally, the spread and acceleration of beach erosion are likely to be met by the proliferation and elaboration of artificial structures such as the heaps of tetrapods which now disfigure long sectors of the coastline of Japan (Walker, 1984), even though it is now clear that such structures promote wave reflection scour, which depletes eroding beaches still further. In the United States, it has been estimated that erosion prevention works now cost at least $US300,000 per kilometre, while artificial maintenance of resort beaches through a one metre sea level rise would require the emplacement of a million cubic metres of sand, costing at least $US3 million per kilometre (Titus, 1986). In the United States and other western countries, the problem will be seen mainly in terms of insurance costs (e. g. through the American National Flood Insurance Program), legislation, compensation, and planning controversies.

Away from highly developed centres there may have to be abandonment of coastal fringes as submergence proceeds, and modification of land and water uses as the water table rises and soil and water salinity increase. Efforts will certainly be made to prevent the sea inundating farmland. The Yilan Plain, in north-east Taiwan, is an example of an already subsiding coastal area where dykes have been built to protect an intensively used lowland from marine invasion (Hsu, 1985).

Estuaries and coastal lagoons are important as breeding and feeding areas for fin and shell fisheries, and management may be required to maintain their productivity as geomorphological and ecological changes accompany the sea level rise.

Consideration of these possible changes in response to the predicted sea level rise may stimulate more research into crops that can be grown in sea water.

Conclusion

The predicted sea level rise during the coming century will greatly modify the geomorphology and ecology of the Estonian coastline, and generate a whole new range of problems for the communities that occupy and utilise these coastal areas. The effects of such submergence can be deduced theoretically, or inferred from studies of the various coastlines where submergence is already in progress because of tectonic subsidence. In Estonia there is a need for site-specific and predictive studies of the geomorphological and ecological consequences of a sea level rise on the coastline, especially those parts that are low-lying, densely-populated, and intensively utilised.

The human response to sea level rise may be counter-measures, where locally available resources and technology can sustain these. The problems of sea level rise in Estonia will be important not only to geomorphologists, ecologists, and social scientists, but also to governments and their agencies concerned with the planning and management of coastal regions. It is hoped that they will consider the implications of the changes outlined in this paper.

CAUSES OF BEACH EROSION

1. Diminution of fluvial sand supply to the coast as a result of reduced runoff or sediment yield from a river catchment (e. g. because of a lower rainfall, or dam construction leading to sand entrapment in reservoirs, or successful soil conservation works).
2. Reduction in sand supply from eroding cliffs or shore outcrops (e. g. because of diminished runoff, a decline in the strength and frequency of wave attack, or the building of sea walls to halt cliff recession).
3. Reduction of sand supply to the shore where dunes that had been moving from inland are stabilised, either by natural vegetation colonisation or by conservation works, or where the sand supply from this source has run out.
4. Diminution of sand supply washed in by waves and currents from the adjacent sea floor, either because the sand supply has run out or because the transverse profile has attained a form which no longer permits such shoreward drifting.
5. Reduction in sand supply from the sea floor because of increased growth of seagrasses or other marine vegetation, which impedes shoreward drifting.
6. Diminished production of sand from sea floor biogenic sources because of ecological changes restricting the production of shelly material.
7. Reduction in sand supply from alongshore sources as the result of interception (e. g. by a constructed breakwater).
8. Increased losses of sand from the beach to the backshore and hinterland areas by landward drifting of dunes, notably where backshore dunes have lost their retaining vegetation cover and drifted inland, lowering the terrain immediately behind the beach and thus reducing the volume of sand to be removed to achieve coastline recession.
9. Removal of sand from the beach by quarrying.
10. Submergence and increased wave attack as the result of a rise in sea level relative to the land.
11. Losses of sand from intensively-used recreational beaches.

12. Increased wave energy reaching the shore because of the deepening of nearshore water (e. g. where a shoal has drifted away, where seagrass vegetation has disappeared, or where dredging has taken place).
13. Increased wave attack due to a climatic change that has produced a higher frequency, duration, or severity of storms in coastal waters.
14. Diminution in the calibre of beach and nearshore material as the result of attrition of beach sand grains, leading to winnowing and losses of increasingly fine sediment from the shore.
15. Diminution in the volume of beach and nearshore material as the result of weathering, solution, or attrition, resulting in the lowering of the beach face and a consequent increase in penetration of wave attack to the backshore.
16. A rise in the water table within the beach, due to increased rainfall or local drainage modification, rendering the beach sand wet and more readily eroded.
17. Increased losses of sand alongshore as a result of a change in the angle of incidence of waves (e. g. as the result of the growth or removal of a shoal or reef, or breakwater construction).
18. Intensification of wave attack as the result of lowering of the beach face on an adjacent sector (e. g. as the result of reflection scour induced by sea wall construction).
19. Migration of beach lobes or forelands as the result of longshore drifting — progradation as these features arrive at a point on the beatch is followed by erosion as they move away downdrift.
20. Removal of a protective sea ice fringe by melting, so that waves reach the beach (e. g. for a longer summer period).

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MEREVEE TASEME TÕUSUST TINGITUD MUUTUSED EESTI MERERANDADEL

Praegu ei kahtle enam keegi, et CO_2 ja teiste inimtekkeliste gaaside kontsentratsioon atmosfääris tingib Maa üleüldise soojenemise ehk nn. kasvuhooneefekti. See omakorda soodustab liustike sulamist ja maailmamere taseme tõusu. Paljude teadlaste arvates tõuseb merevee tase aastaks 2050 0,24—1,17 meetrit. Juba praegu on kindlaks tehtud, et Maa keskmine temperatuur on viimasel sajandil tõusnud 0,4 °C võrra. Üha kasvav ja süvenev mererandade abrasioon paarikümne viimase aasta jooksul viitab aga sellele, et ka meretaseme tõus on juba alanud. Tormide sagenemistki võib seletada globaalsete kliimamuutustega. Artiklis on juttu sellest, kuidas meretaseme muutus mõjub randade geomorfoloogiale ja ökoloogiale nii Eestis kui ka mujal maailmas.

Э. БЭРД

ПОДНЯТИЕ УРОВНЯ МОРЯ И СВЯЗАННЫЕ С ЭТИМ ИЗМЕНЕНИЯ НА ЭСТОНСКОМ ПОБЕРЕЖЬЕ

В настоящее время никто не сомневается в том, что концентрация CO_2 и других антропогенных газов в атмосфере обусловливает общее повышение температуры Земли, т. н. парниковый эффект. Это в свою очередь благоприятствует таянию ледников и общему подьему уровня Мирового океана. По мнению многих исследователей, уровень океана к 2050 году может повыситься от 0,24 до 1,17 м. Установлено, что за последнее столетие средняя температура Земли увеличилась на 0,4 °C. В то же время все возрастающая абразия морских берегов указывает на то, что подъем уровня океана уже начался. Увеличение количества штормов также можно объяснить глобальными изменениями климата. Высказывается мнение о том, каким образом изменения уровня моря могут повлиять на морфологию и экологию Эстонии и других регионов земного шара.