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Ground beetles as 'early warning-indicators' in restored salt marshes and dune slacks

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Abstract

Populations of ground beetles and spiders are continuously monitored since 1990 in the dunes and salt marshes of the river Ijzer estuary (Belgium), where a recent nature restoration project took place within the framework of LIFE. Immediately after restoration measures, continuous (year cycle) pitfall and window trapping was performed during several years in restored or newly developed salt marsh and dune slack habitats and compared to target ('old' salt marsh) habitats. In this paper, we focus on ground beetle assemblages and species quality from these samplings, based on some 40,000 beetles identified to 96 species. Results show several beetles new to the study area as well as a marked increase of several target species with high conservation interest (Red-list species). However, many of these species could be rapidly lost again unless natural dynamic processes are kept ongoing. Historical beetle data show that many species that disappeared from the area during the past century have not yet been able to recolonise. This is especially true for salt marsh species and possibly due to dispersal limitation. Many dune slack species re-appeared but did not establish viable populations. Moreover, several ground beetle species indicate increased sand instead of silt deposits in new and old salt marshes. Further invertebrate monitoring therefore is a prerequisite for a well-founded long-term evaluation of the executed nature development measures. Such monitoring will be of much interest, both for an evidence-based nature conservation management, for fundamental ecological research, but also as a possible early warning system for the need of additional management measures in the future.

1 Introduction

1.1 History of the river Ijzer estuary: a story of continued habitat destruction

The relatively small river Ijzer is located in the western part of Belgium and has a short intertidal zone at the North Sea. A short history of this area is summarised on Fig. 1, comparing the most important phases of habitat destruction and degradation that took place from early medieval time until about 1986. About 1200, the estuary still consisted of many creeks, vast areas of salt marshes, extensive coastal dunes and, probably, many biologically very interesting dune-salt marsh transitions. By the end of the 18th century (as derived from the maps of de Ferraris, 1775), large natural areas had been lost, especially of salt marshes, mainly due to the limitation of sea tidal influences up to the sluices that had been constructed by that time besides the port of Nieuwpoort (situated at the lower right). Recent historical maps show an ongoing reduction of salt marsh area about 1842. At the beginning of the 20th century, when tourism along the Belgian coast started to expand, the first large areas of dunes were urbanised, along with the complete loss of the salt marsh along the left bank of the river. By 1955, habitat loss reached dramatic proportions, then also along the right bank of the Ijzer and prominently in the associated coastal dune area. A naval port was constructed and dunes were further reduced mainly due to building activities and camping sites. Moreover, a large part of the already highly reduced salt marsh was covered with dredged materials from maintenance channel deepening projects of the river. Shortly after that period, a new marina was constructed to the south of the persisting salt marsh relic, which was then even further reduced due to renewed deposition of dredging material on its northern remnants. Nevertheless, the highly reduced natural remains of the estuary still contained many organisms of high conservation interest, including many invertebrate species of the Red Data Book. We therefore started a long-term ecological study of spiders and ground beetles in the area, on one of the few remaining sites left along our coast with at least some continuous gradients between seafront and inland dunes as well as a salt marsh relic.

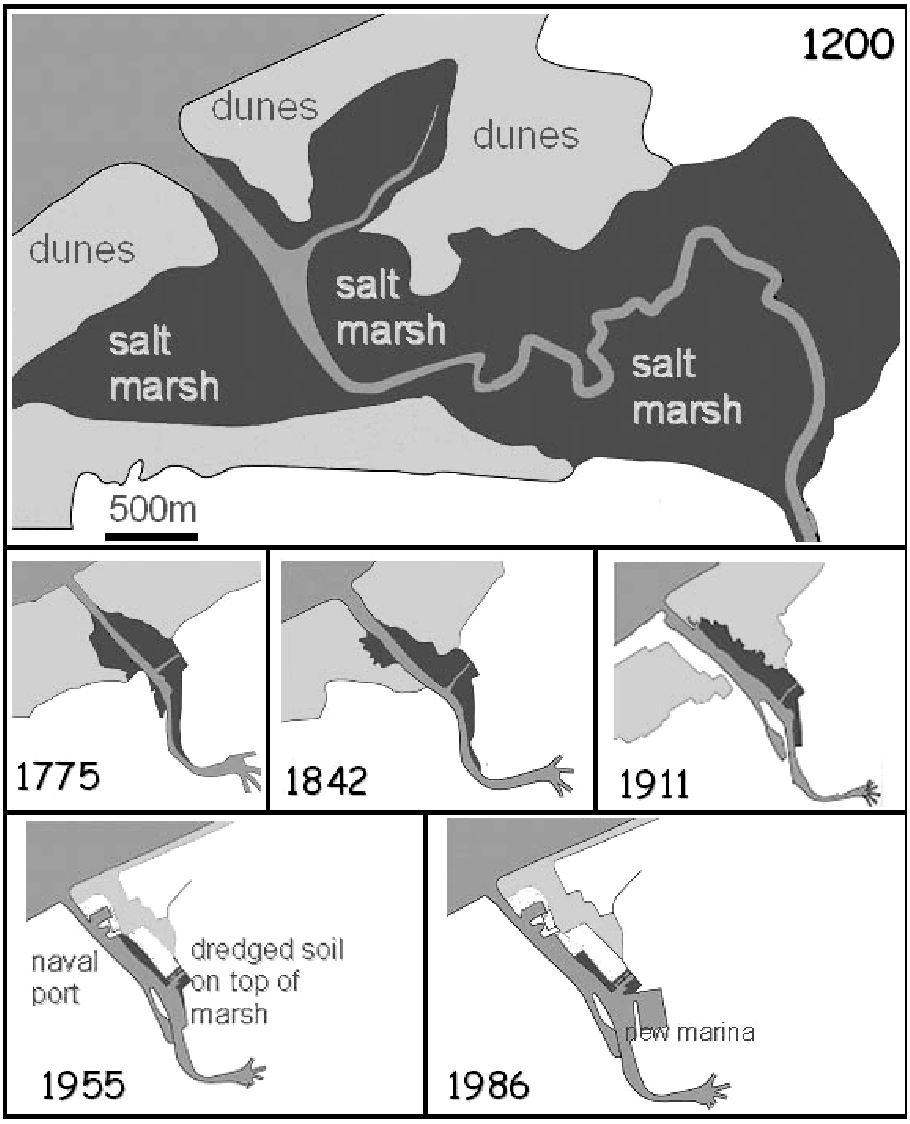

Figure 1: A short history of the river Ijzer estuary, illustrating the main episodes of destruction and degradation of salt marsh and dune habitats until the situation before the recent nature restoration project (all maps are drawn at approximately the same scale) (modified, after: Decleer et al. 1995, Verhulst 1995).

1.2 Long-term invertebrate studies in the river Ijzer estuary

Since 1989, we have been continuously monitoring ground beetle and spider populations in the river Ijzer estuary coastal dunes and salt marsh (Belgium), mainly by means of uninterrupted long-term pitfall trapping on several sites. From this unique study area, along the right bank of the Ijzer estuary and the seaside beach front, no less than 140 ground beetle species are hitherto known based on these continuously performed samplings (Desender 1996, 2005b, Desender & Baert 1995). Diversity and assemblages have been studied on different scales by means of different sampling techniques, including pitfall traps, window traps, and air bell traps. The area moreover has been a favourite location for many entomologists from about 1850 onwards, especially during the past century. Therefore, many historical data also exist on the former beetle fauna of this area. Most of this historical material is housed in the RBINSc (Brussels) and we recently completely checked and summarised these data in a distributional database.

Our long-term ecological study, as well as the presence of even older historical beetle data, offer an ideal framework to monitor and evaluate the effects of a recent nature restoration project that was started by the Flemish Government in 1998-2001 in the same area, within the framework of LIFE (Hoffmann 2004, Hoffmann et al. 2005, Maelfait et al. this volume). The general aim was to restore or create the natural ecological gradients typical for a coastal estuarine ecosystem. Most energy and restoration measures have therefore been directed towards an important increase of the pre-existing limited surface of old salt marsh, as well as towards increasing contact zones between mud flats, salt marsh, and coastal dune habitats. The project aims at restoring the situation of the Ijzer estuary around the beginning of the previous century, i.e. a period that is documented at least to a certain degree concerning the nature values (including ground beetles) of the area.

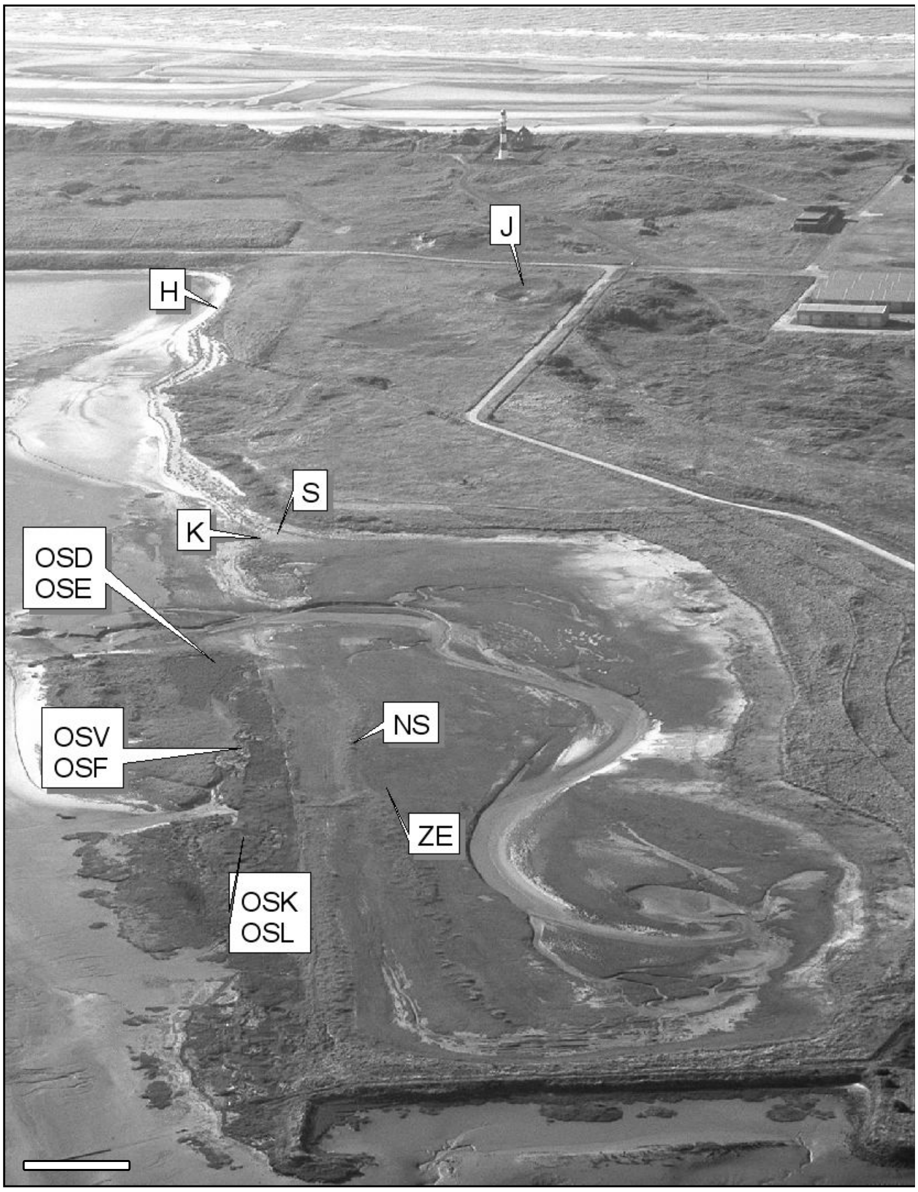

Figure 2: Recent aerial view of the river Ijzer estuary study area, including a new dune slack (site J) at the margins of a dune pond, and the old salt marsh relic (lower left with OS sites), separated by a low dike from new salt marsh (sites, H, K, S, NS, ZE); scale bar ~50 m.

In order to evaluate the effects of this recent restoration project, we sampled newly created or modified sites (dunes, dikes, banks of a dune pond and new salt marsh), while continuing our long-term sampling on a number of reference sites from the main target habitats in the area. Spider and beetle results of additional area-covering (short-term) sampling campaigns are reported elsewhere (Desender et al. 2006).

In this contribution, we focus on ground beetle assemblages and species quality from restored or newly developed salt marsh and dune slack habitats, based on 26 continuous (complete year cycle) trapping series collected on 12 sampling sites. Sampling sites are illustrated on a recent aerial view of the area in Fig. 2 and include old salt marsh (OS sites), new salt marsh (sites H, K, S, NS, ZE) and a new dune slack on the margins of a dune pond (J). Colonisation and turnover of assemblages are continuously monitored in these newly created sites and in the corresponding target habitats in order to evaluate the results of the restoration measures.

2 Results

2.1 Ground beetle assemblage and indicator species analyses in old and more recent salt marshes and dune slack during different sampling years

About 40,000 ground beetles, belonging to 96 species, were identified from the 26 year-cycles used in this paper. Based on the quantitative data for the most numerous species, a Detrended Correspondence Analysis (DCA) was performed with PCORD (McCune & Mefford 1999), after transforming data to relative densities within each species over the different sampling series (i.e. equal weighting each species). To prevent possible overruling noise from accidental species in this analysis, only carabid species with 26 or more individuals (equalling at least the number of separate sampling series used) were retained. A total of 42 ground beetle species fulfilled this criterion. Test runs with a more or less strict criterion nevertheless yielded a similar ordination as compared to the result for the 42 species, representing more than 95 % of the total pitfall and window trap catches. We refer to Maelfait et al. (this volume) for more information on this type of analysis and the rationale behind the use of pitfall data. Four of the analysed year-cycles are based on window trap catches and were entered as separate series in the analysis.

Figure 3 shows the ordination plot of year-cycle samples scores (upper graph, with overlay of main habitat type) and added species scores (lower graph) from this analysis. Based on the major groups of sampling series observed in this ordination (cf. added ellipses and overlay), the ground beetle species and their abundance are re-ordered in two-way Table 1 (number of individuals per series based on three sampling units or traps). Within each of the groups, sample series are ordered according to sampling year. An Indicator Value (IndVal) analysis (Dufrêne & Legendre 1997) was performed based on this data and testing the hypothesis of indicator species for the four groups of samples (i.e. dune slack, window trap series, new salt marsh and old salt marsh). These results, along with the observed significance for each species indicator value, are presented in Table 2. Species with a statistically significant IndVal for one of the tested groups are also indicated in Table 1.

Along the first DCA ordination axis, we can easily discriminate three different groups of sites/series based on their ground beetle assemblages (Fig. 3): four consecutive year cycles in the developing dune slack vegetation (J01-J04) are regrouped at the left, whereas all 'old salt marsh' series cluster to the right. Early stages of developing new salt marsh as well as all window traps year cycles (two from the dune slack, two from new salt marsh) are found in more or less central position. Along the second axis, data on flying ground beetles (window traps) are discriminated from all pitfall trapping series, whereas at the same time dune slack samples are clearly positioned according to the year of sampling (2001 up to 2004, i.e. from the very first stages of development of the newly created site up to a more developed dune slack vegetation).

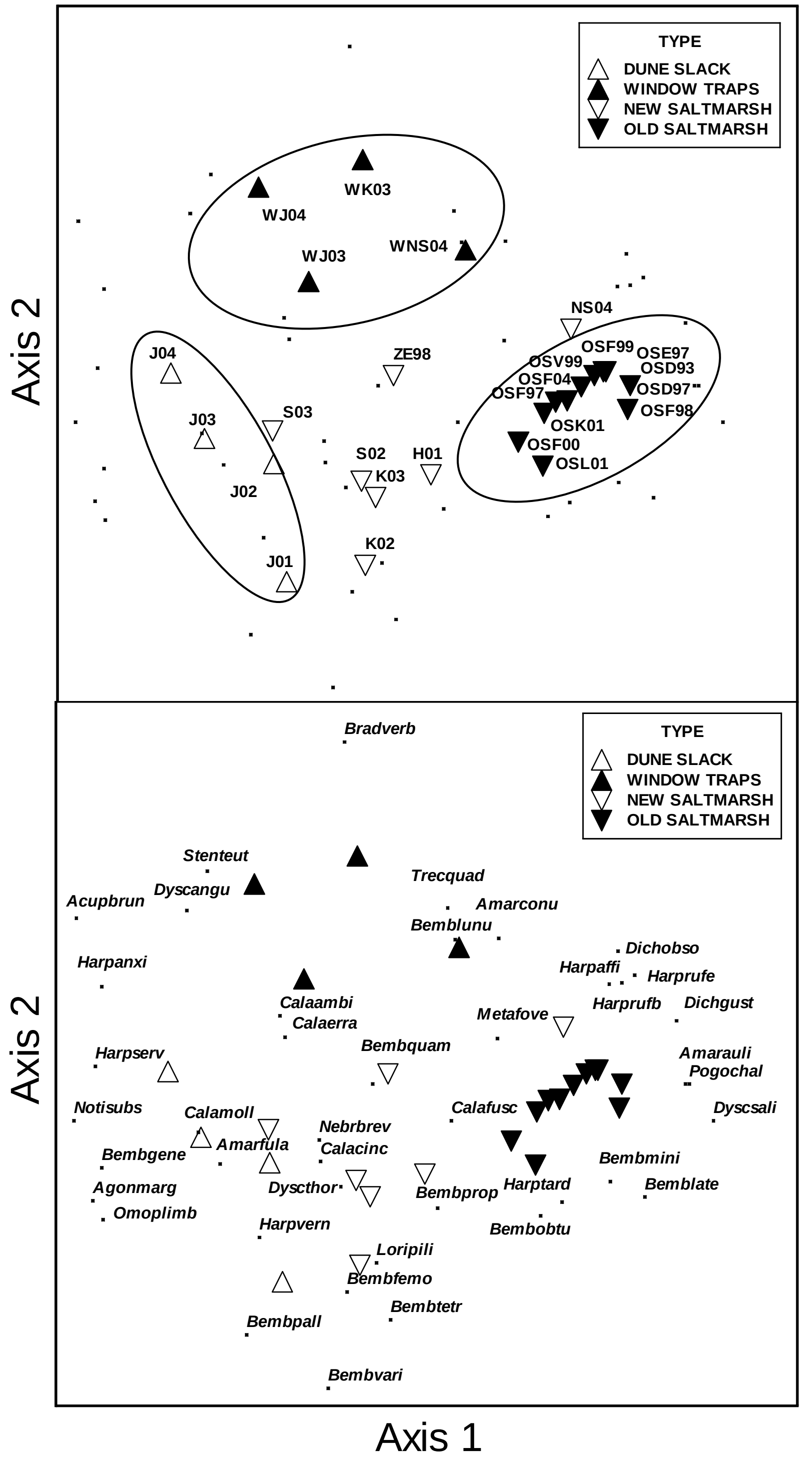

Figure 3: Plot of DCA ordination (detrended by 26 segments) sample and species scores, based on 26 site-year samples for the 42 most abundant ground beetle species: upper graph with added site labels and ellipses regrouping most important habitats/samples, lower graph with abbreviated species labels (see Table 2 for explanations).

Table 1: Re-ordered two-way table showing the number of ground beetles per species (corrected to three sampling units per series) in the 26 sampling series (site code followed by year of sampling between (19)93 and (20)04; preceded by 'W' for window trap catches) used for DCA (species names given in full in the same order in table 2); species in grey box have a significant Indicator Value for their respective group of sampling series, cf. table 2).

species	J01	J02	J03	J04	WJ03	WJ04	WK03	WNS04	ZE98	H01	S02	K02	K03	S03	NS04	OSD93	OSD97	OSE97	OSF97	OSF98	OSF99	OSV99	OSF00	OSK01	OSL01	OSF04	
Agonmarg	**5**	**14**	**83**	**29**							2																131
Calamoll	**6**	**117**	**159**	**227**				3	20	21	2	2	5	7	27			5	2		4	1				1	607
Harpvern	**2**	**8**	**3**	**8**						3		2	1	1				1	1								29
Notisubs		**5**	**8**	**26**								2		2													41
Omoplimb	**98**	**113**	**146**	**276**																							632
Bembpall	**504**	**95**	**56**	**8**			3		18	4	29	9	3														728
Nebrbrev	**1**	**9**	**11**	**21**					9		1		3	1		5	1	2		5	2	2			4		77
Bembgene		**3**	**3**	**17**								2	2														26
Dyscthor	**302**	**927**	**1496**	**803**					484	19	99	150	377	110	1106	2	34	62	18	79	18	57	46	600	130	186	7103
Amarfula		**12**	**26**	**15**					6		2		8	8	2												78
Harpanxi		**11**	**15**	**62**		3	1		1				1	2				1								2	98
Acupbrun		**2**	**42**	**455**	42	141																					681
Harpserv		**1**	**20**	**54**							2		1	2		1		1	1							1	83
Dyscangu	**3**	**3**	**21**	**51**	3	12	18			1	6		1	9	2												130
Calafusc	2	23	14	18					29	5		2	6	5	1	4		40	15	25	3						190
Calaambi		17	26	63					74	1				1	15			1			2						199
Calacinc	5	20	14	27					45	47	3			3		2	1	1	2	1	1				1		172
Calaerra		18	54	101					145				14	2	15			3		4	1	2	1			2	361
Bembvari	15	2			3			6				41	2														68
Bradverb					**3**	**12**	**33**	**9**											1				1	2			61
Trecquad		1		2	**3**	**30**	**27**	**165**	23	10	5	5	2	1	12		2	6	5		4		4				305
Stenteut			5	53	15	12	18	6					2	1													111
Bemblunu	5	8	5		18	9	21	6		13	2	18	6		6			4	2	2	6		8	27	10	16	190
Amarconu							9	54	42			6	2		33	2		2			4		1				155
Bembfemo	36	90	63	2	3		12	3	**430**	**146**	**117**	**284**	**320**	**44**	**21**	1	1	2	1	4		1	1		2	1	1584
Bembquam		2		2	9	6	6	9	**4**	**27**	**2**	**14**	**21**	**2**	**2**	1								1		1	107
Loripili			2	2						6			11	2	1										4		27
Bembtetr	2	15	24	3					1	31	9	77	35		2			1		6	7		45	1	8		266
Harpaffi			3	5					39	6			3	2	227	9	3	17	4	6	15	1	2			21	363
Bembobtu	1	2								36	14	2		1	3	1	2	4	11	9	13	1	18	3	2		122
Bembprop	1	3	5	2	3					30			12	2		3		1	1	3	1	1		9	2	1	79
Pogochal										3	5	35	8	2	2096	**1391**	**826**	**1659**	**560**	**2396**	**1050**	**270**	**142**	**347**	**504**	**1656**	12948
Dyscsali																**7**	**4**	**66**	**2**	**72**	**3**		**2**	**3**	**15**	**4**	178
Amarauli		1							1								**3**	**3**	**2**	**9**	**6**	**3**	**1**				29
Bemblate										3		5	6		3		**6**	**10**		**39**		**1**	**1**	**29**	**24**	**4**	131
Harptard	3	3								2						3	1	4	4	5				3	1	1	30
Dichgust					1		18	54	2					1	1913	154	218	1097	239	418	645	129	189	176	250	97	5601
Bembmini	3	2	3	2	2	3	9	6		232	3	185	230		646	146	32	105	144	206	341	7	89	33	70	829	3326
Harprufb	2	2	1				3			4						1	1	23	2	12				3			53
Harprufe							9		16				3		54	10	4	5	9	12	20	3	5	2		16	168
Dichobso	1						3	609		4	2	2		1	741	67	91	324	92	180	267	74	34	56	30	29	2606
Metafove		1		1					11	2							1	4	1	1	1	1	2				26
total	993	1522	2301	2327	105	228	190	930	1400	656	300	836	1078	212	6928	1810	1231	3454	1119	3494	2414	554	592	1293	1057	2868	39890

Table 2: IndVal (IV) analysis based on four groups corresponding to DCA results (compare with table 1); Maxgrp= group identifier for group with maximum observed IV: 1= dune slack, 2= window trap catches, 3= new salt marsh, 4= old salt marsh; (*)= proportion of randomised trials with indicator value equal to or exceeding the observed indicator value; p= (1 + number of runs >= observed)/(1 + number of randomised runs); significant values in bold.

			IV from randomised groups		
Species	**Maxgrp**	**Observed Ind Val**	**Mean**	**S.Dev**	**p (*)**
Agonum marginatum	1	**99.3**	23.4	11.98	**0.0010**
Calathus mollis	1	**90.3**	41.7	13.46	**0.0010**
Harpalus vernalis	1	**81.8**	27.5	11.18	**0.0010**
Notiophilus substriatus	1	**71.2**	22.5	11.41	**0.0010**
Omophron limbatum	1	**100.0**	19.1	10.33	**0.0010**
Bembidion pallidipenne	1	**94.5**	34.9	14.17	**0.0020**
Nebria brevicollis	1	**72.6**	31.8	10.30	**0.0030**
Bembidion genei	1	**69.7**	22.6	11.57	**0.0030**
Dyschirius thoracicus	1	**66.4**	38.8	9.26	**0.0080**
Amara fulva	1	**59.0**	24.8	11.06	**0.0110**
Harpalus anxius	1	**69.1**	33.7	14.39	**0.0120**
Acupalpus brunnipes	1	**54.8**	22.9	11.61	**0.0150**
Harpalus servus	1	**71.2**	35.3	14.85	**0.0200**
Dyschirius angustatus	1	**64.0**	31.6	11.88	**0.0200**
Calathus fuscipes	1	48.6	31.1	9.81	0.0580
Calathus ambiguus	1	49.8	28.7	12.47	0.0720
Calathus cinctus	1	52.1	35.1	11.93	0.0960
Calathus erratus	1	46.6	36.2	13.30	0.1970
Bembidion varium	1	16.7	25.4	12.72	0.7740
Bradycellus verbasci	2	**97.8**	26.6	13.56	**0.0010**
Trechus quadristriatus	2	**84.1**	46.7	14.35	**0.0050**
Stenolophus teutonus	2	46.6	26.2	11.81	0.0630
Bembidion lunulatum	2	43.8	32.6	7.05	0.0780
Amara convexiuscula	2	27.8	29.9	12.78	0.4710
Bembidion femoratum	3	**78.5**	44.4	10.81	**0.0030**
Bembidion quadrimaculatum	3	**54.3**	34.0	11.30	**0.0560**
Loricera pilicornis	3	39.6	24.0	11.81	0.0770
Bembidion tetracolum	3	48.3	34.6	11.25	0.1150
Harpalus affinis	3	**58.2**	47.1	15.61	0.2480
Bembidion obtusum	3	39.2	35.9	11.18	0.3370
Bembidion properans	3	23.4	38.0	12.24	0.9480
Pogonus chalceus	4	**76.2**	33.4	9.97	**0.0020**
Dyschirius salinus	4	**90.9**	31.5	13.41	**0.0050**
Amara aulica	4	**54.9**	26.0	10.57	**0.0190**
Bembidion laterale	4	**59.3**	30.9	11.34	**0.0220**
Harpalus tardus	4	38.4	26.2	9.88	0.1030
Dicheirotrichus gustavii	4	52.9	37.4	11.74	0.1150
Bembidion minimum	4	48.6	43.0	9.08	0.2410
Harpalus rufibarbis	4	33.9	30.9	12.44	0.3240
Harpalus rufipes	4	34.6	32.0	11.49	0.3360
Dicheirotrichus obsoletus	4	30.3	39.7	11.48	0.7890
Metabletus foveatus	4	19.0	30.3	12.38	0.8330

An array of typical ground beetle species for each of the observed clusters of sampling series can be derived from the lower DCA graph as well as from the IndVal analysis and the ordered table with raw data, taking knowledge on the ecology of each species and its possible preference for other dune habitats into account. The last-mentioned aspect is especially important for the small-sized dune slack site, where several ground beetles from other (dry dune) habitat types were observed in relatively large numbers (e.g. the typical marram dune species *Calathus mollis*, the dune grassland species *Calathus ambiguus*, *Calathus cinctus*, *Harpalus vernalis* and *H. anxius*). This suggests the occurrence of more or less strong edge effects and/or source-sink effects, an aspect dealt with in more details by Maelfait et al. (this volume).

The most typical carabid species for the dune slack (margins of new dune pond) were, among others *Agonum marginatum*, *Omophron limbatum*, *Bembidion pallidipenne*, *B. genei*, *Dyschirius thoracicus* and *Acupalpus brunnipes*. The last-mentioned species was also caught in large numbers during flight activity. Some of these species gradually build up a large population, whereas others have already nearly completely disappeared again from the area (e.g. *Bembidion pallidipenne*). *Bradycellus verbasci* and *Trechus quadristriatus* appeared most numerously in the window trap catches. Indicator species for early stages of new salt marsh development were *Bembidion femoratum* and *B. quadrimaculatum*, whereas *Pogonus chalceus*, *Dyschirius salinus,* and *Bembidion laterale* were most numerous in old salt marsh samples. A number of other salt marsh species occurred both in old salt marsh, some window trap series and most of the somewhat more developed 'new' salt marsh sites: *Bembidion minimum*, *Dicheirotrichus gustavii,* and *D. obsoletus*. Assemblages, derived from the most recent new salt marsh series (NS04), therefore were already much more similar to 'old salt marsh' series as compared to earlier stages of developing new salt marsh. Nevertheless, the typical ground beetle salt marsh species *Dyschirius salinus* was still absent from restored or new sites.

2.2 Evaluating nature restoration based on historical and recent occurrence of dune slack and salt marsh ground beetles in the river Ijzer estuary

The river Ijzer estuary received already much attention in the past and repeatedly was visited by entomologists from about 1850 onwards. This old data, residing in the RBINSc collections (Brussels, Belgium), enables us to compare, for this area, the historical and recent occurrence of ground beetle species that are known as typical dune slack or salt marsh species.

Table 3 summarises this data and regroups, for each of the main target habitats, dune slack or salt marsh, the ground beetle species that are documented to have disappeared in historic times from the area (most recent year of observation mentioned), most probably as a consequence of the habitat destruction and degradation that took place mainly during the past century (1A and 2A species). A comparison with species that continuously remained present in the area or even appeared as 'new' during or since the recent nature restoration project (1B and 2B species) shows a strongly differing pattern depending on whether species are typical for dune slack or for salt marsh. All mentioned dune slack species (14) without exception have been observed in recently restored sites, whereas less than half of the salt marsh species (9 out of 20) managed to colonise or recolonise the area.

Most, if not all, of the very special carabid species that were lost in historical times from the area (some 20 species, a large majority of these seriously threatened in our region), were not or not yet able to re-establish viable populations in the Ijzer estuary restored habitats (cf. table 3, persistence in study area of 1A and 2A species). Salt marsh species with a preference for more coarse-grained sediments or with a wider range of preferred soil types (sand/silt), appear to show less problems in maintaining viable populations (several 2B species), also in restored sites.

Table 3: Typical dune slack and salt marsh ground beetles, with their historical and/or recent occurrence in the river Ijzer estuary, regrouped into (A) species that disappeared from the area before the onset of recent nature restoration and (B) those that have been continuously present or recently appeared as new to the area, along with quantitative data on their recent occurrence in the estuary, Red Data Book category for the region of Flanders (Desender et al. 1995), persistence in the area, and major soil type preference.

group	*species*	preferred habitat	year with most recent observation before restoration project	observed on recently restored sites	red data book category	persisting in study area	preferred soil type
1A	*Bembidion argenteolum*	dune slack	1883	2 ind.	**rare**	**NO**	sand
	Bembidion doris	dune slack	1850	1 ind.	not threatened	NO	sand
	Bembidion pallidipenne	dune slack	1938	abundant	**near-extinct**	**??**	sand
	Broscus cephalotes	dune slack	1926	2 ind.	not threatened	NO	sand
	Cicindela maritima	dune slack	1945	1 ind.	**endangered**	**NO**	sand
	Dyschirius obscurus	dune slack	1937	1 ind.	**rare**	**NO**	sand
	Omophron limbatum	dune slack	1909	abundant	not threatened	YES	sand
1B	*Acupalpus brunnipes*	dune slack	new to area	abundant	**vulnerable**	**YES**	sand
	Agonum marginatum	dune slack	continuosly present	abundant	not threatened	YES	sand
	Bembidion velox	dune slack	new to area	3 ind.	**rare**	**NO**	sand
	Bradycellus distinctus	dune slack	continuosly present	abundant	**rare**	**??**	sand
	Dyschirius thoracicus	dune slack	continuosly present	abundant	not threatened	YES	sand
	Elaphrus riparius	dune slack	continuosly present	abundant	not threatened	YES	sand
	Stenolophus teutonus	dune slack	continuosly present	abundant	not threatened	YES	sand
2A	*Anisodactylus poeciloides*	salt marsh	1880	1 ind.	**extinct**	**NO**	silt
	Bembidion ephippium	salt marsh	1934	NO	**vulnerable**	**NO**	silt?
	Bembidion fumigatum	salt marsh	1937	NO	**rare**	**NO**	silt
	Bembidion iricolor	salt marsh	1997	NO	**rare**	**NO**	silt
	Bembidion maritimum	salt marsh	1979	NO	**endangered**	**NO**	silt
	Bembidion normannum	salt marsh	1947	NO	**vulnerable**	**NO**	silt
	Dyschirius chalceus	salt marsh	1883	NO	**rare**	**NO**	silt
	Dyschirius impunctipennis	salt marsh	1949	NO	**extinct**	**NO**	silt?
	Pogonus littoralis	salt marsh	1875	NO	**near-extinct**	**NO**	silt
	Pogonus luridipennis	salt marsh	1865	NO	**probably threatened**	**NO**	silt
	Pterostichus macer	salt marsh	1982	NO	**rare**	**NO**	silt
2B	*Amara convexiuscula*	salt marsh	continuosly present	abundant	**rare**	**YES**	silt/sand
	Bembidion laterale	salt marsh	continuosly present	abundant	**probably threatened**	**YES**	sand
	Bembidion minimum	salt marsh	continuosly present	abundant	not threatened	YES	silt
	Bembidion nigropiceum	salt marsh	new to area	2 ind.	**new to fauna**	**NO**	sand
	Bembidion varium	salt marsh	continuosly present	abundant	not threatened	YES	silt
	Dicheirotrichus gustavii	salt marsh	continuosly present	abundant	**rare**	**YES**	silt
	Dicheirotrichus obsoletus	salt marsh	continuosly present	abundant	**rare**	**YES**	sand
	Dyschirus salinus	salt marsh	continuosly present	NO	**rare**	**??**	silt
	Pogonus chalceus	salt marsh	continuosly present	abundant	**rare**	**YES**	silt/sand

3 Discussion

Habitats of newly created, restored or developed sites in the Ijzer estuary (dikes, dunes, salt marsh as well as banks of freshwater habitats), can be characterised, during their first years of existence, by a large number of ground beetle species, typical for strongly disturbed habitats, more specifically for cultivated fields and ruderal sites on light soil. *Trechus quadristriatus* and *Bembidion femoratum* indeed prefer poorly vegetated disturbed sand to sandy loam soils, such as on cultivated fields, but also occur in rather wet situations such as highly dynamic riverbanks (Turin 2000). These ground beetles are excellent flyers and therefore were also abundant in our window trap catches in differing habitats (cf. Desender 2000).

In addition, an important number of Red Data Book species have been observed in these new or restored habitats. These include many typical dune and salt marsh species, occurring in the immediate surroundings, but also several dune slack species, recolonising the study area, such as *Bembidion pallidipenne* (near-extinct in Flanders) and *Bembidion argenteolum* (threatened). Another typical species for first stages of sandy riparian or dune slack habitats is *Omophron limbatum*, preferring margins of fresh or brackish water bodies of high quality, especially devoid of vegetation, including early stages of succession of coastal dune slacks. The first-mentioned beetle is extremely rare in our country and until now, it was only known from very few coastal locations. *Bembidion pallidipenne* appears to colonise nearly exclusively the first stages of brackish-fresh water riparian sites, particularly without vegetation, such as dynamic early stages of dune slacks. It needs constantly present dynamics and turnover in order to maintain a long–term surviving metapopulation structure. The species occurred in massive numbers in the Ijzer estuary during the first years after restoration measures. At present, this ground beetle has already disappeared nearly completely from the study area again, which could have important implications for options concerning future nature conservation management. Future monitoring will enable to conclude whether or not the individuals of such species are making up permanent (well-established) populations or, alternatively, only a temporary population, as a result of quickly changing habitat ecological characteristics or as a result of source-sink effects from adjacent high-quality habitats (cf. Maelfait et al., this volume). Such effects could especially manifest themselves in years with high abundance of particular species.

These beetles nowadays only persist in very few nature reserves of our region, but are typical pioneer species from coastal freshwater-brackish waterside habitats on sandy soil, such as dune slacks and dune-salt marsh transitions. Such species in general possess an excellent dispersal power (cf. Desender 1989a) and apparently rapidly colonised the new habitats that became available in the Ijzer estuary. To survive in the long run, they will need relatively continuously present dynamics at ecosystem level as well as sufficient populations functioning in a larger metapopulation. Many of these ground beetles however only occurred or were abundant during or immediately after the restoration measures took place, quickly disappearing after that initial stage. The rapidly decreasing numbers of *Bembidion pallidipenne*, after being initially very abundant on the new dune slack, are highly illustrative in this context. To conclude, many of these highly specialised dune slack beetles did not manage to establish more continuous and viable populations in the river Ijzer estuary.

In North-Western Europe, ecological restoration of salt marshes, assisting the recovery of degraded, damaged or destroyed salt marsh (SER 2004), has received increasing attention during recent years, mainly within the context of de-embankments and realignment of coastal defences (Garbutt et al. 2006, Wolters et al. 2005b). The recent nature restoration project in the river Ijzer estuary involved, related to wet target habitats, the removal of a large amount of top soil in order to recreate potential sites for salt marsh development and dune-salt marsh transitions, adjacent to an old salt marsh relic. As part of this project, a dune pond was created, giving rise to accompanying dune slack vegetation along its margins. At the onset of this recent nature restoration project, less than 4 ha of salt marsh remained in the area from about 60 ha that were present about a century ago (Goetghebeur 1976), while only one dune slack, moreover in late successional stage, occurred in the neighbouring dune area.

Restoration success in other salt marsh or dune slack studies has mostly been evaluated by plants or birds and there are only very few investigations that also used information on terrestrial invertebrates in this context. Yet invertebrates offer unmatched possibilities for such studies, being extremely diverse, with many highly specialised organisms and useful at small as well as larger scale. Native arthropod assemblages are abundant and considered functionally important in many ecosystems, and certainly in wet dune slacks and salt marshes (Gratton & Denno 2005). Successful restoration of (benthic) invertebrate communities of salt marshes has been reported to require consideration of both habitat (ecological) characteristics and dispersal ability of target species, even in created sites in close proximity to natural source areas (Armitage & Fong 2004, Warren et al. 2002).

Ground beetles are documented from about 1850 in the river Ijzer estuary and have been studied in detail and monitored continuously, along with spiders, for about the past 20 years (Baert & Maelfait 1999, Desender 1996, Desender et al. 1992, 2006). The study area has been recognised as a biodiversity hotspot, at least to recent Belgian standards, but is hoped to become even more interesting in the future. The large array of typical ground beetle species that disappeared from the area in historical times and have not yet been able to recolonise, points to a major problem of dispersal limitation. This is certainly true for salt marsh species and yet, somewhat paradoxically, nearly all of these species are known to possess a high dispersal power (Desender 1989a). In this process of recolonisation, availability and short distance of potential source areas are obviously of major importance, combined with the role of coincidence. Many of the most typical dune slack and salt marsh beetles from our region indeed are highly mobile as an adaptation to unstable conditions and inundation risks in the highly dynamic habitats they prefer (Desender 1989a, for interesting exceptions to this pattern, see also Desender 2005a, Desender et al. 1998, Dhuyvetter et al. in press). Typical dune slack invertebrates, as well as plants, therefore rely for their successful establishment on regular dispersal from other natural areas with persisting young dune slack successional stages (Bossuyt et al. 2003, Bossuyt & Hermy 2004, Desender et al. 1998, Esselink et al. 2000, Wolters et al. 2005a). To conclude, regional factors are crucial for a successful colonisation and establishment in nature restoration sites.

Our results in the nature restoration sites of the Ijzer estuary show the importance of such regional processes for ground beetles from dune slacks and salt marshes, be it at somewhat differing scales. Several rare or threatened ground beetles from mud flats and salt marshes, surviving in the salt marsh relic of our study site, *Pogonus chalceus*, *Dicheirotrichus obsoletus*, *D. gustavii* and *Bembidion laterale*, rather quickly expanded their populations in the adjacent, newly created, salt marsh areas, especially during the most recent year included in the above-mentioned analyses (2004). This is not or not yet the case for the species *Dyschirius salinus* and could be due to a lack of sufficient clay in the substrate of the new marshes. This beetle indeed is adapted to a very fine-structured salty substrate and avoids sandy sediments (Desender 1989A, Turin 2000). On the other hand, the relatively high abundances on newly created sites of species preferring more coarse-grained sediments, such as *Bembidion laterale* and *Dicheirotrichus obsoletus* (in contrast to the congeneric species *D. gustavii*, more typical for heavier soils), also point into the same direction. These beetles clearly prefer a more sandy substrate as compared to many other salt marsh or halophytic carabids (Desender 1989a). However, when comparing, at a larger scale, the actual salt marsh communities observed today to the extended list of carabid species that have been lost during the past century from the Ijzer estuary, the result is not yet very positive. Not a single of these salt marsh ground beetle species managed to (re)colonise the area yet. This strongly suggests a negative influence of dispersal limitation, in other words the lack of high quality salt marsh areas at sufficient proximity that could act as source areas for the re-establishment of species that disappeared during the past century from our study area.

Dune slack species in our region seem not (yet) to suffer much from such dispersal limitation, as most of the species recorded historically have already attempted to recolonise the restored sites of the river Ijzer estuary. There are indeed several dune slack areas of high interest at relatively shorter distances along the Belgian West coast, as compared to a complete lack of potential salt marsh source areas in this region. Unfortunately, only few of these colonisation attempts by dune slack carabid species resulted in successful establishment of populations, which might be linked to the fast succession taking place in restored habitats, and/or the lack of sufficient dynamics, possibly also related to relatively small restoration scales, certainly applying to the restored dune slack.

Sedimentation characteristics on restored sites impose further constraints on colonisation and successful establishment of ground beetles, because most of these beetles prefer specific soil conditions (Turin 2000). Many authors have acknowledged the importance of sand/silt balances in sedimentation for the outcome, and long term effects of recovery of restored salt marshes or dune slacks, thereby also stressing the need for long term strategic monitoring of indicator organisms (Crooks et al. 2002, Garbutt et al. 2006, Hughes & Paramor 2004, Mendelssohn & Kuhn 2003, Lammerts et al. 2001, Olff et al. 1997, Pethick 2002). Related to this, dredged material has been proposed for soil subsidy in order to combine dredging needs with coastal marsh rehabilitation and restoration (Weinstein & Weishar 2002). Long term monitoring of salt marsh or dune slack organisms also was mentioned as crucial in view of actual and future climate change and sea level rise (Lammerts et al. 2001, Olff et al. 1997, Weis & Weis 2003). Our results show that ground beetles appear to be excellent candidates as early warning indicators or monitoring tools in all of these contexts.

We obviously have documented the very first stages only of the development of restored and new sites in the Ijzer estuary. Some earlier studies have referred to the time and conditions needed for successful restoration of salt marsh communities: rapid recolonisation is expected for pioneer and low-marsh species; provided they are occurring in nearby source areas and restored sites are at appropriate altitude (Bernhardt & Koch 2003, Wolters et al. 2005B). Gratton & Denno (2005) reported a rapid recovery of native arthropod assemblages associated with restored brackish marshes after the removal of invasive *Phragmites australis*, but it is unclear how far such results can be generalised without reference to a regional-specific situation (see also Eertman et al. 2002, Weis & Weis 2003). Vegetation of restored wet dune slacks did not yet reach a stable state after 5 years (Grootjans et al. 2001). Brackish wetland vegetation and soil characteristics have been reported to take up to 90 years or even more than 200 years to develop and become equivalent to natural marsh (Craft et al. 2002). It is therefore necessary to continue our monitoring of old and new habitats of the Ijzer estuary nature reserve as a prerequisite for a well-founded long-term evaluation of the performed nature development measures. Moreover, further monitoring is of high fundamental scientific interest against the background of our long-term sampling data on beetles and spiders, sampling which is continued without interruption on several sites in this estuary. This should enable us in the future to make a clear distinction between directed changes in the area (mainly as a consequence of ecological processes, accompanying measures for conservation management) and changes due to year-to-year population dynamic fluctuations (whether stochastic or not) in carabid beetle or spider populations.

Another important aspect that was not yet taken into account in the current monitoring concerns population genetics of a number of target invertebrate species. To this end, we have formerly studied, on a regional scale, a number of ground beetles and other terrestrial arthropods for their genetic diversity and differentiation in salt marshes, including the Ijzer estuary marshes (cf. Desender 1985, 1989A, B, Desender et al. 1998, Desender & Verdyck 2001). It would be of much interest to repeat such studies in the future for species that occurred earlier in the area or not, in order to compare population genetics from newly created or restored populations to those from the old salt marsh relic or to those from other (potential source) areas. Such population genetic information not only might enable to the tracing of the origin of colonising species, but also could be of major importance to judge population viability in the long run.

Our results, less than five years since nature restoration measures were taken, show a number of new ground beetle species and assemblages, but warrant that many of these could be rapidly lost again unless natural dynamic processes are kept ongoing. It is, moreover, still unclear whether the newly created salt marsh habitats will evolve as hoped for, because of the observation that newly deposited sediments in this salt marsh are relatively coarse-grained (sand instead of silt), whereas, at the same time, the old salt marsh remnant seems to be more and more under the influence of sand deposits.

Moreover, many salt marsh species, present in the area about a century ago, did not re-appear yet, strongly suggesting dispersal limitation. To conclude, ground beetles appear once again as powerful ecological indicators. Further invertebrate monitoring is therefore imperative not only for a better understanding of the patterns and processes generated by the nature restoration measures, but also as a possible early warning system for the need of additional management measures in the future.

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