Supplementary materials and methods

1. Geological setting
Many previous studies describe in detail the stratigraphic architecture of the Po-Adriatic Sea systems, especially for the latest Quaternary (e.g., [1–8]). Here we provide a brief outline focused only on the main stratigraphic features of the targeted area. For an in-depth discussion of stratal geometries and environmental evolution of the investigated succession, we refer to the above-mentioned papers and references therein.

The Pliocene-Quaternary sedimentary infill of the basin beneath the Po coastal plain is >7 km thick and records a stacking of 3rd order tectono-stratigraphic sequences bounded by major unconformities, each representing a major event of deformation related to the structuring of the Apennine foredeep [7,9]. High-resolution studies of the latest Quaternary succession of the study region [10,11] documented a set of higher frequency (4th order) wedge-shaped packages of strata, in which internal organization was interpreted as being driven primarily by glacio-eustatic changes. Within the study area, the topmost 40-m-thick succession has been interpreted to represent the Last Glacial Maximum (LGM) depositional sequence [3]. The sequence boundary was placed at a notable paleosol developed at the beginning of the last maximum glacial phase (<34 kyr cal BP [2]). The lowstand systems tract (LST) is mainly composed of laterally extensive sand fluvial bodies associated with pedogenically modified floodplain deposits. The onset of an overall retrogradational stacking pattern (represented by a vertical transition from coastal to marginal marine facies) highlights the transgressive surface (TS) or maximum regressive surface. The TS, being associated with a weakly developed palaeosol attributed to the Younger Dryas cold spell, is the most distinct surface that can be recognized regionally in cores [8]. Above the TS, the Holocene deposits of the Po coastal plain record a transgressive-regressive, wedge-shaped succession, recently subdivided in a series of centennial units embedded into eight millennial-scale depositional units (parasequences in [3]). Parasequences 1 to 3 show a distinct retrogradational stacking pattern of alluvial to estuarine and marginal marine depositional systems in tune with a stepped post-glacial eustatic sea-level rise.
Parasequences 4 to 8, in turn, are characterized by a multifaceted and aggradational to increasingly progradational pattern of coastal/deltaic depositional systems. The maximum flooding surface, marking the turnaround between transgressive and normal regressive stacking patterns, is interpreted to be at the base of parasequence 4 ([3]; figure S1).

To track the lateral variation in the stratigraphic distribution of species along the depositional dip and strike, we focused on four cores forming a 35-km-long L-shaped transect across the southern Po Plain (figure S1). The two proximal (updip) cores (204-S7 and 205-S5) located in proximity to the maximum extent of Holocene marine ingression are dominated by floodplain, coastal swamp and brackish (lagoon/bay) facies associations. The downdip cores (205-S9 and 205-S14) represent a more distal setting, ~18 km seaward from the shoreline during the maximum ingression, and record transition from brackish, through nearshore to shallow-marine depositional environments.

2. Resampling models
We designed two null models aimed at separating the effects of random range truncations, stratigraphic trends in fossil abundance, and facies control on species occurrence. The first model makes two assumptions: random distribution of species and uniform sampling intensity (constant number of individuals sampled per horizon) throughout the stratigraphic succession. The second model relaxes the second of those assumptions by allowing the sample size to vary vertically according to the trends in fossil abundance actually observed in the cores. The assumption of random distribution of fossils made by both models corresponds to a scenario in which either (1) the probability of species occurrence is uniform across all facies (i.e. species lack any environmental preferences and their preservation potential is the same in all environments), or (2) sedimentary environment remains constant though time.

For both models, all samples in a given core were first pooled together. For each core depth corresponding to an actually sampled horizon, a random sample of individuals was taken from this pool without replacement, while preserving their species identities. In the first model, the number of randomly drawn individuals was constant and equal to the average sample size in the core. In the second model, the number of specimens was set to be the same as actually observed at the particular core depth. Such random samples were assigned to all horizons sampled in the core. The simulated dataset was then used to construct a range chart and identify the stratigraphic positions of LOs for each species. This procedure was repeated 10,000 times. Repeated simulations indicated that analytical outcomes were highly reproducible at 10,000 iterations.

The number of LOs that was actually observed at each sampled stratigraphic horizon was compared to the median number of LOs at that depth calculated across all resampling iterations. The corresponding 95% confidence intervals were calculated using the percentile method [12]. The observed pattern of stratigraphic range end-points was compared to the null expectation by first ranking all species in simulated range charts according to their LOs and then calculating for each rank the median core depth at which the LO occurred together with corresponding 95% confidence intervals.

3. Inferring time and pattern of extinctions from fossil occurrences
We tested whether the effects of sequence-stratigraphic controls can be removed by methods that correct for the Signor–Lipps effect by estimating the time or pattern of extinctions from fossil occurrences under a simple model of uniform preservation and recovery of taxa. As noted by Wang & Marshall [13], this class of probabilistic methods continue to dominate palaeontological analyses,
including the most recent studies. Whereas several methods relaxing the assumption of uniform fossil recovery has been proposed (e.g., [14–18]), they remain rarely used in empirical studies [13]. A systematic evaluation of different statistical approaches used to estimate times of extinction from stratigraphic data is beyond the scope of our study (see reviews in [13,19]).

(a) Assessing the pattern of extinctions. We applied a simple graphical method proposed by Meldahl [20] to distinguish between gradual, stepwise, and sudden extinction patterns based on the relationship between stratigraphic abundance and position of LO (figure S4). Stratigraphic abundance is the proportion of stratigraphic intervals (core samples in our case) in which a given species was observed. Because the magnitude of artificial truncation of stratigraphic ranges is likely to be smaller for common taxa (i.e., those with high stratigraphic abundance), their LOs should better approximate the stratigraphic positions of extinction events. Simulations suggest that gradual, stepwise, and sudden extinction pattern produce different graphical relations between stratigraphic abundance and LO [20]. This method implicitly assumes that probability of collecting a taxon is constant throughout a stratigraphic section. However, if a given species is tied to a specific facies, both its stratigraphic abundance and the position of the LO may primarily reflect the stratigraphic distribution of that facies.

We supplement the qualitative approach of Meldahl [20] with a formal test of the null hypothesis of the simultaneous extinction of all species using the likelihood ratio test of Wang and Everson [21]. The null hypothesis is true in our hypothetical scenario: given that all species found in the cores are known to be extant in the region, their true stratigraphic range-end points correspond to the modern sedimentary surface. We also applied the recently proposed generalization of this method [22], which directly estimates the number of extinction pulses. In both cases, species recorded only once in a given core were excluded prior to the analyses. For each core, we calculated the relative support for extinction scenarios ranging from a single (i.e., simultaneous extinction) to five extinction pulses (figure S5) using the original R code provided in the supplementary material to Wang and Zhong’s [22] paper.

The two-step algorithm of Wang and Zhong [22], first determines the maximum likelihood estimate (MLE) for each possible number of pulses. In the second step, MLEs for different number of pulses are compared using Akaike information criterion (AIC) and Bayesian information criterion (BIC). To increase the accuracy of the estimated number of pulses, a $k$-nearest neighbour classifier is applied to the set of AIC and BIC weights (see [22] for details). The algorithm predicts the number of extinction pulses most consistent with the observed fossil occurrences under the assumption of uniform preservation and recovery of fossils throughout the extent of their stratigraphic ranges. It also estimates the confidence level associated with each number of pulses, which can be interpreted as posterior probabilities in Bayesian framework.

(b) Confidence limits on stratigraphic ranges. We compared the performance of two methods for calculating confidence intervals on the position of the true end-points of stratigraphic ranges: the classical method of Strauss and Sadler [23], which assumes random occurrence and thus constant sampling probability of fossil, and its generalization [15], which allows recovery potential to vary with stratigraphic position according to a predefined recovery function. We estimated species recovery functions using multivariate ordination [24] (see below). For species with at least four occurrences in a given core, we calculated 50% and 95% confidence intervals using both methods (figures S6 and S7) and compared the proportion of taxa for which the estimated range end-point fell below the topmost sample in the core (the extinction horizon in our hypothetical scenario).
We calculated the stratigraphic length (measured in thickness of strata) of the confidence interval ($r_c$) as a fraction ($\alpha$) of the observed stratigraphic range ($R$) [19,23]:

$$r_c = \alpha R$$  (1)

This fraction depends on the number of horizons at which a taxon was found ($H$) and on the chosen confidence level ($C$) [23]:

$$\alpha = (1 - C)^{-\frac{1}{H-1}} - 1$$  (2)

As demonstrated by Marshall [15], equation (1) can be generalized as the relationships between the probability of collecting a taxon within its known stratigraphic range ($R$) and the probability of observing it within a distance ($r_c$) beyond that range. These probabilities can be expressed as integrals of the fossil recovery potential curve [15]:

$$\int_b^{b+r_c} f(h)dh = \alpha \int_a^b f(h)dh$$  (3)

where $a$ is the stratigraphic position of the first occurrence of a taxon, $b$ is the position of the LO, $\alpha$ is given by equation (2), and $f(h)$ is the density distribution function of fossil recovery potential, i.e. the function describing how the probability of collecting a taxon varies with stratigraphic position.

Calculation of generalized confidence intervals requires establishing fossil recovery potential of a species. Following Holland [24], we estimated sample-level collection probabilities for each species using a multivariate ordination technique, detrended correspondence analysis (DCA). DCA places samples and species in the same ordination space in a way that maximizes the compositional variation in the dataset along the first ordination axis. DCA axis 1 scores can be thus considered as a measure of the relative position of samples along the primary environmental gradient controlling taxonomic composition of the assemblages. In marine settings axis 1 usually corresponds to water depth and environmental variables that are correlated with it [25,26]. Parameters of species response curves, which describe how the probability of collecting a given species changes along this gradient, can be estimated from DCA results using a simple Gaussian model [24,27,28]. The model is based on three parameters: preferred environment (PE; mean of the Gaussian curve), environmental tolerance (ET; standard deviation of the Gaussian curve), and peak abundance of a species (PA; the probability of finding the species at its PE represented by the height of Gaussian curve). PE can be estimated by the DCA axis 1 score of the species, ET by the standard deviation of axis 1 scores of all samples containing the species, and PA by the proportion of samples in which the species was found located within one ET of the PE of that species (see [24] for further details).

DCA ordination of the total dataset was performed with R package “vegan” [29]. Prior to the analysis, samples that were devoid of fossils or contained only a single species, as well as species occurring in only one sample were removed [28], resulting in the dataset containing 83 species and 143 samples. The relative abundance data were log-transformed to down-weight the effects of very abundant species. In the resulting DCA ordination samples tend to be distributed along axis 1, according to their position along the onshore-offshore gradient (figure S8). Specifically, samples representing swamp and lagoon/bay facies associations tend to have negative axis 1 scores, beach ridge/delta front samples have intermediate scores, and prodelta and offshore transition samples have high axis 1 scores. Higher axis 1 scores can be thus interpreted as indicating an increase in marine influence and/or water depths. Moreover, axis 1 scores of species are positively correlated with their preferred water depth ($r = 0.50$; 95% confidence interval: 0.28–0.68; $P < 0.001$). The correlation is weaker then observed in the previous quantitative bathymetric models for Po Plain Quaternary succession [4,11]. This reflects our focus on species rather than genera (used in the
previous studies), inclusion of rare taxa, and a large share of samples from the proximal cores (204-S7 and 205-S5). These onshore cores capture predominately floodplain and back-barrier habitats, in which assemblage composition is controlled by environmental factors that can be poorly correlated with water depth, like salinity [4,30].

Based on the above evidence, DCA axis 1 can be used as a quantitative proxy for tracking shifts in the position of each core along the onshore-offshore gradient throughout the stratigraphic succession (figure S9). Probability of collecting a species from a given sampling horizon can be estimated based on the axis 1 score of that sample and species response curves derived from the DCA. These estimates can be used to track stratigraphic changes in species recovery potential (figure S9B) and thus allow for estimating the generalized confidence intervals on stratigraphic ranges [24]. For a given species, we summed recovery potential across all sampling horizons that were located within the observed stratigraphic range of the species. The resulting sum was multiplied by factor $\alpha$ [as defined in equation (2)] to obtain the total recovery potential expected within the extent of a confidence interval $r$, above the observed range [equation (3)]. To find the top of the confidence interval we cumulatively added recovery potentials for samples located above the observed LO of a species, from the lowermost to the highest sampling horizon, until the summed recovery potential was greater than or equal to that recorded within the observed range [31]. The stratigraphic position of the last sample included in this procedure marked the top of the confidence interval. If the sum of recovery potentials across all samples located above the LO of a species, including the topmost sample in the core, was still smaller than the total recovery potential within the observed range, we assumed that the confidence interval extends beyond the modern sedimentary surface. This procedure was done separately for each of the four cores.

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Figure S1. Location of the investigated cores (a) and cross-section of the latest Pleistocene–Holocene succession of the Po coastal plain (b; based on [3] and unpublished data of L. Bruno and B. Campo) illustrating the regional facies architecture and sequence-stratigraphic framework. Millennial-scale parasequences are numbered in red. See figure 1 for the key to sequence stratigraphic units.
Figure S2. Tangled-fence diagram showing variation in the timing of LOs across individual cores. Lines connect stratigraphic positions of the LO of a single species in different cores. Only species recorded in more than one core are shown. Shading delineates approximately isochronous core intervals correlated based on the parasequence framework (see [3] for details). In the two distal cores (205-S9 and 205-S14), individual parasequences cannot be distinguished around the MFS due to strong condensation. This condensed interval (shaded in dark gray) correlates with the more stratigraphically expanded interval in the proximal cores that encompasses multiple parasequences ranging from the upper part of parasequence 2 to the parasequence 6. PS 1, parasequence 1; PS 2a, lowermost part of the parasequence 2; CI, condensed interval; PS 7, parasequence 7; PS 8, parasequence 8.
Figure S3. Stratigraphic trends in fossil abundance (number of identifiable specimens per sample; a, d) in cores 204-S7 and 205-S14, and the results of two resampling models for the expected number of last occurrences (b, e) and distribution of stratigraphic range end points (c, f). See figure 3 for further details and figure 1 for the key to sequence stratigraphic units.
Figure S4. Plots of stratigraphic abundance (proportion of samples in which a species was recorded) versus the stratigraphic position of last occurrence support stepwise extinction pattern in three of the studied cores. In core 205-S14 the observed distribution in more consistent with a gradual extinction scenario. See figure 1 for the key to sequence stratigraphic units.
Figure S5. Maximum likelihood estimates for the positions of extinction pulses in each core for scenarios involving 1–5 pulses (upper rows) and corresponding confidence levels (lower rows) calculated using the two-step algorithm of Wang and Zhong [22]. Species recorded only once in a given core were excluded prior to the analyses. With the exception of core 205-S5, stepwise extinction scenarios are overwhelmingly better supported compared to a single extinction event.
Figure S5. Stratigraphic ranges with their 50% (diamonds) and 95% confidence intervals (triangles) for mollusc species with at least four occurrences in a given core. Confidence intervals were calculated using the classical method of Strauss and Sadler [23], which is assuming random occurrence and thus constant sampling probability through the taxon’s range. The percentage of species for which the 95% confidence interval do not reach the topmost sample in a given core ($Pr$) is also shown. Note, that since all species are extant, the resulting range extensions of all species should reach the top of the succession (dashed horizontal line; the position of a sudden extinction event in our hypothetical scenario).
Figure S7. Stratigraphic ranges with their 50% (diamond) and 95% confidence intervals (triangles) for mollusc species with at least four occurrences in a given core. Confidence intervals were calculated following the procedures of Holland [24] by using sample-level estimates of species occurrence rates derived from the DCA ordination of the complete dataset. The percentage of species for which the 95% confidence interval do not reach the topmost sample in a given core ($Pr$) is also shown. Although, this approach yield improved estimates comparing to classical confidence intervals (figure S6), it tends to underestimate the ranges of taxa confined to the transgressive sand sheet in the two distal cores, suggesting that mixing of ecologically non-overlapping species in these deposits hampers the correct estimation of the parameters of their response curves. For 13 species (marked in red), the parameters of response curves, and consequently the confidence intervals on their stratigraphic ranges, could not be estimated from the ordination results. The DCA axis 1 scores of these species lie far outside the observed range of sample scores, which may indicate that their preferred habitat is not represented in the studied cores [28].
Figure S8. Detrended correspondence analysis (DCA) ordination of samples (a) and species (b) based on log-transformed relative abundance data. Samples tend to be distributed along the DCA axis 1 according to their position along the onshore-offshore gradient, with higher axis 1 scores corresponding to stronger marine influence or greater water depths. Samples in (a) are colour-coded according to the depositional environment. See Dataset S1 for the numerical codes of species.
Figure S9. Stratigraphic patterns in DCA axis 1 sample scores along the four cores (a) and examples of recovery potential curves (b) for two species of corbulid bivalves (*Lentidium mediterraneum* and *Varicorbula gibba*) with contrasting environmental preferences. Note that the recovery potential of these species is neither constant, nor changing monotonically along the sedimentary succession. The observed fossil occurrences are shown to the left of the recovery potential curves (filled dots). In the distal cores (205-S9 and 205-S14), the two species co-occur within the condensed deposits below the MFS containing ecologically mixed faunal assemblages. See figure 1 for the key to sequence stratigraphic units.