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Rapid (10-yr) recovery of terrestrial productivity in a simulation study of the terminal Cretaceous impact event

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Abstract

Investigations of short-term (up to 10^3 yr) environmental change across the Cretaceous–Tertiary boundary provide evidence for reduced temperatures, consistent with the injection of debris and sulphate aerosols into the upper atmosphere by a large impact event. Concomitant with this was a postulated massive addition of CO_2 to the atmospheric carbon reservoir by impact vaporisation of the Chicxulub carbonate platform. Taken together, a high CO_2 but low irradiance environment would have created unusual conditions for the operation of the terrestrial biosphere. Here, we have evaluated this environmental influence on terrestrial ecosystems using a process-based dynamic global vegetation model forced with post-impact global climates, derived by modification of the GENESIS atmospheric climate model simulation for the latest Cretaceous. Our results suggest that terrestrial primary productivity initially collapsed and then recovered to pre-impact levels within a decade. Global terrestrial carbon storage in vegetation biomass exhibited a similar collapse but complete recovery took place on a 60–80 yr timescale. The recovery of both terrestrial net primary productivity and vegetation biomass was largely mediated by the high CO_2 concentration stimulating ecosystem photosynthetic productivity in the warm low latitudes. An apparently rapid recovery of terrestrial ecosystem function stands in marked contrast to the situation for the marine realm, where the organic carbon flux to the deep ocean was suppressed for up to 3 million years.

Keywords: global change; K-T boundary; impacts; models; recovery; vegetation

1. Introduction

Overwhelming evidence now exists for the terminal Cretaceous impact of a large asteroid on the Yucatan peninsula [1–3]. Environmental changes inferred to result from the impact event are thought to include a short-term (< 1 yr) low temperature excursion, owing to the injection of large quantities of light attenuating debris from the impact crater into the upper atmosphere [4–6], and soot production from global wildfire [7]. In the longer term (< 10^3 yr), more moderate cooling, driven by sulphate aerosol loading of

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the upper atmosphere and owing to impact vaporisation of the Chicxulub anhydrite, ensued [8]. Concomitant with global cooling is a postulated massive addition of CO_2 by impact vaporisation of the Chicxulub carbonate platform [9]. The cooling indicated by geological data implies that atmospheric loading of dust, soot and sulphate aerosols overrode any CO_2-related greenhouse warming in the short term [10].

Here we quantitatively assess the effects of these environmental conditions on the terrestrial biosphere using a process-based dynamic global vegetation model (DGVM) [11] forced with post-impact environmental datasets derived from the GENESIS global climate model simulation of the latest Cretaceous [12]. The dynamic nature of the DGVM allows an assessment to be made of the response time of terrestrial ecosystems to changes in the global environment following a Cretaceous–Tertiary (K/T) boundary impact event. We simulated the immediate effects of the impact on terrestrial ecosystems with two different scenarios because of uncertainty about the extent of the dust cloud, and therefore its climatic effects [4–8]. The first case assumes the dust cloud and its climatic effects were distributed globally ('worst-case' scenario) and the second assumes it to have been rapidly (within a year) confined to a narrow latitudinal band around the equator ('best-case' scenario).

Following these two simulations of the initial effects of the impact winter, we then quantified the influence of the ensuing post-impact environment over the next century on ecosystem net primary productivity (NPP) and carbon storage in vegetation biomass. These results are considered in relation to climatic and CO_2 effects on the functioning of ribulose-1,5 bisphosphate (Rubisco), the primary carboxylating enzyme in C_3 plants, the context of the floral extinction patterns [13–18], and the rate of ecosystem recovery in the marine realm [19,20].

2. Materials and methods

Pre-impact terrestrial net primary productivity and carbon storage in vegetation biomass were determined using the University of Sheffield process-based DGVM [11], which simulates under steady-state conditions of climate and atmospheric composition (CO_2 and O_2) the basic plant processes of photosynthesis, respiration and stomatal control of transpiration. The DGVM includes a dynamic coupling with the Century biogeochemical model [21], which describes the cycling of carbon and nitrogen in soils, thereby closing the terrestrial carbon cycle. Surface litter inputs (leaves and roots) from the vegetation model are decomposed through the various Century routines to compute soil nutrient status, which in turn feeds back and influences NPP. Equilibrium model solutions are achieved by iterative coupling between the vegetation and biogeochemistry models. As in other Mesozoic simulations [22], the Century model was unmodified. Model predictions of plant, canopy and ecosystem processes show close agreement with measurements from a worldwide range of sites [11] and a whole catchment experiment with CO_2 enrichment and warming [23].

Vegetation dynamics in the DGVM are captured by simulating competition between five different functional types (evergreen needle-leaved trees, evergreen broad-leaved trees, deciduous needle-leaved trees, deciduous broad-leaved and understorey herbs) [24]. At any given site, the probability that a particular functional type will achieve dominance over competing functional types is controlled by temperature and the duration of the growing season, i.e. the number of days with net photosynthetic carbon gain. As the growing season shortens moving polewards, the deciduous leaf habit dominates with site minimum temperatures controlling leaf type (i.e. broad-leaf or needle-leaf form). Each functional type can tolerate a specific range of climatic conditions, as defined from a wide range of field observations [25]. Where these climatic ranges merge, the functional type that is closest to its optimal growth conditions achieves dominance.

Coupled with competition being governed by climate is an element of physical competition between each functional type. Where climatic conditions are suited to one or more functional types, functional types that are fastest growing (i.e. have the highest NPP) trend towards dominance over time due to their ability to outcompete neighbouring functional types for resources. In all of these simulations we have assumed no important functional types of plants became extinct over the K/T boundary [13,26]. The functional type approach is taken in all global-scale vegetation model simulations to avoid the need to define the physiological characteristics of all plant species ($\sim$250 000).

The global post-impact environment, used to force the DGVM, was derived as follows. The amount of CO_2 injected into the atmosphere [9] can be calculated, to a first approximation [9], from the estimated size of the K/T bolide (12 km diameter) [27], the category of bolide (asteroid) [3] and the depth of the target carbonate terrace (3 km) [2]. This yields a total mass of 10 000 Gt C (equivalent to 5000 ppm CO_2, assuming 1 ppm $\equiv$ 2 Gt C) supplemented by emissions from wildfire. Global wildfire is thought to have burned c. 25% of the above-ground biomass in the latest Cretaceous biosphere [7,28] releasing c. 256 Gt C ($\equiv$128 ppm) into the atmosphere (i.e. 25% of the latest Cretaceous vegetation carbon pool [29]). Therefore, atmospheric CO_2 for the impact year, and the subsequent 100 years, was increased from the pre-impact value of 580 ppm to 5700 ppm (Table 1).

A GCM simulation of a K/T-sized impactor using modern geography and fine (1 μm) dust indicates land surface temperatures initially drop by an average of 13°C and 99% of the dust injected into the atmosphere settles out after 1 year allowing at least 85% of sunlight to reach the land surface [4]. There is uncertainty whether this climatic cooling, and complete blockage of incoming solar radiation, occurred globally, so we modelled two climates for the year of impact (i.e. year zero). The 'worst-case' climate assumed the dust cloud was uniformly spread throughout the upper atmosphere, causing a complete global reduction in irradiance and lowering of temperatures by 13°C. The 'best-case' climate assumed these impact-related effects were concentrated in the tropics owing to irradiance and temperature being reduced between 30°N and 25°S. To simulate the effects of global wildfire during year zero, as indicated by geochemical analyses of K/T terrestrial and marine sediments [7], the fire model embedded within the DGVM [30] was adjusted to burn 25% of the vegetation carbon within any given pixel.

A GCM simulation [5] indicates that the global climate system recovered slowly with mean annual temperatures (MATs) around 6°C below normal after 1 year [5]. Sulphate aerosols, formed from the vaporisation of the Chicxulub anhydrite, are distributed globally, prolonging the period of cooling [6] and, depending on their mass, can take up to 100 years or more to be removed from the stratosphere. They cause a reduction in sunlight at the land surface of 10–75% [6]. Spatial heterogeneity in the cooling is expected [4,5] but is not well constrained, because the particle size and optical properties of the dust cloud and sulphate aerosols are poorly understood [4,5]. Therefore, in the 100 years following the impact, the latest Cretaceous MATs and irradiance were reduced at all latitudes by 6°C and 30% respectively within the DGVM (Table 1).

We have not explicitly included the destructive

Table 1
Summary of environmental change resulting from the K/T boundary impact event and used to simulate the responses of the terrestrial biosphere

Scenario[a]	Atmospheric CO_2 concentration (ppm)	Temperature change (°C)	Irradiance (% reduction)
'Worst-case' applied globally	5700 (5700)[b]	−13 (−6)	100 (−30)
'Best-case' applied between 25°N and 30°S	5700 (5700)[b]	−13 (−6)	100 (−30)

See text for the discussion and derivation of each climatic feature. Values are those used to simulate year zero (impact year) and in parentheses the 100-year interval following the impact.
[a] CO_2, temperature and irradiance adjustments were applied as described for year zero (impact year) and then globally for the ensuing 99 years.
[b] Assumes 100 years is too slow for significant oceanic CO_2 uptake and CO_2 removal from the atmosphere by silicate and carbonate rock weathering.

effects of the shock wave following the impact because, from a consideration of crater size and estimated impact energy [27], the total blast wave area is estimated at 1.1×10^7 km^2. This represents c. 2% of the Earth's surface, only a small fraction of which is land. Also not explicitly considered are the effects of impact-produced 'acid rain' on ecosystem structure, productivity and carbon storage, as these effects cannot at present be incorporated into numerical models. Instead, our simulations quantify the effects of known changes in the environment on the well understood physiological and biogeochemical processes involved in the terrestrial carbon cycle.

3. Results and discussion

The resulting time series of global terrestrial productivity shows a crash at year zero following imposition of the K/T impact winter due to reductions in temperature and irradiance and increased biomass burning, with a subsequent recovery in the post-impact environment occurring within a decade (Fig. 1a). The rapid recovery of global NPP occurred regardless of whether the climatic effects of the dust cloud were realised globally ('worst-case') or within a narrow latitudinal band around the equator ('best-case'). Ultimately, global NPP in the environment envisaged for the century following the K/T impact event marginally exceeded that of the latest Cretaceous (Fig. 1a). This result arose in the simulations because the effects of a high atmospheric CO_2 environment on canopy development and photosynthetic carbon gain overrode the negative effects of global cooling and lowered irradiance. The fern-spore spike, characteristic of many terrestrial K/T boundary sections in the western interior of North America, provides evidence for the first phase of terrestrial plant re-colonisation [26,31]. The dominance of ferns in the post-impact landscape was short-lived, with angiosperms rapidly re-establishing dominance implying a rapid recovery in ecosystem productivity, in support of our model predictions. This apparent rapid recovery of terrestrial NPP contrasts markedly with the marine situation where the export of carbon from the surface water to deep ocean was suppressed for up to 3 million years as new species evolved at multiple trophic levels [19,20].

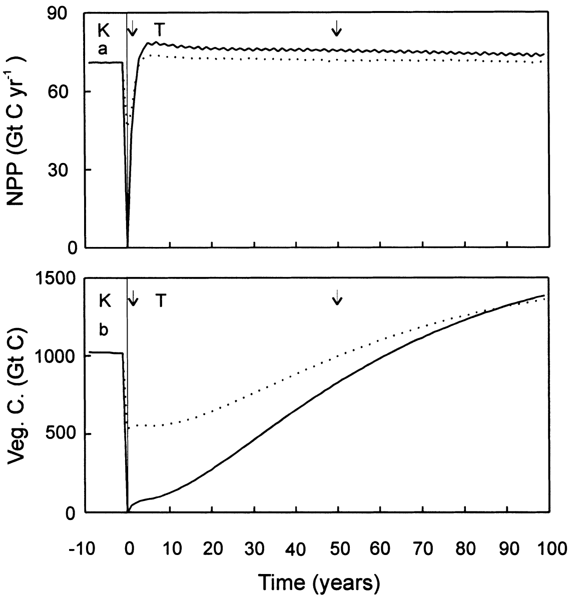

Fig. 1. Time series of changes in (a) annual global terrestrial NPP and (b) carbon storage in vegetation biomass for the 'worst-case' (solid line) and 'best-case' (broken line) simulations. Vertical arrows indicate year datasets extracted for latitudinal transect analysis in Fig. 3. K = Cretaceous; T = Tertiary.

Carbon storage in vegetation biomass also shows a major drop immediately after the K/T impact event and this is followed by a slower rate of recovery than primary production, with values surpassing those of the latest Cretaceous situation after 60–80 years (Fig. 1b). This integrated global response reflects temporal changes in the relative dominance of the different functional types to environmental changes across the K/T boundary. For the first decade after the impact, all of the functional types, except understorey herbs, showed carbon losses relative to the pre-impact situation (Fig. 2a). This results from increased biomass burning as well as the cool temperature, low irradiance conditions limiting photosynthetic productivity. Carbon storage in understorey herb biomass increases however, because of the onset of succession in that first decade in the burned areas (Fig. 2a). In the 'best-

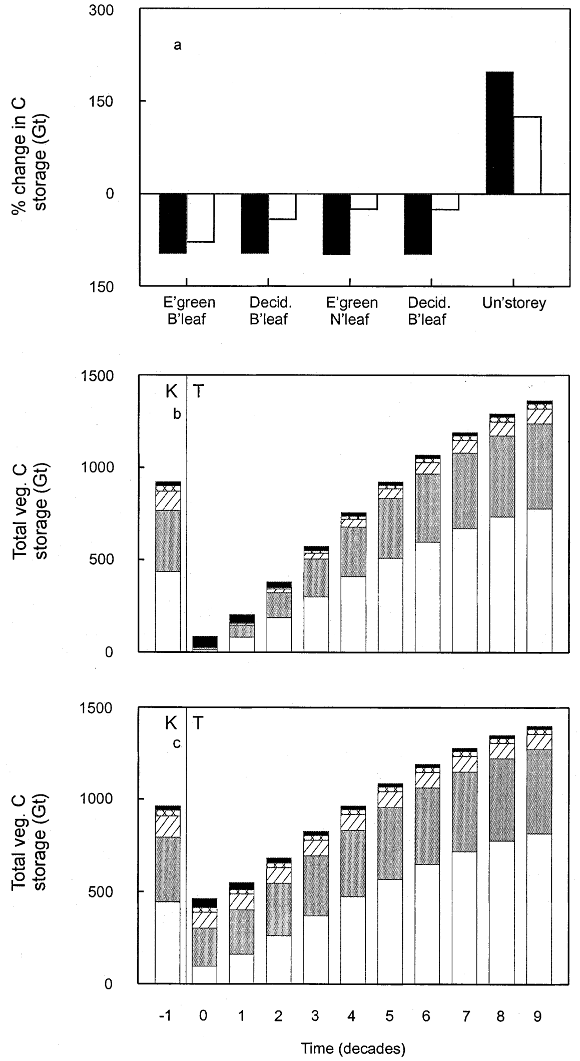

Fig. 2. (a) Percentage change in carbon stored in vegetation biomass for the 'worst-case' (solid bars) and 'best-case' (open bars) scenarios one decade after the K/T boundary impact. Total of carbon stored in the biomass of each functional type (decadal averages) for 'worst-case' (b) and 'best-case' (c) scenarios respectively (evergreen broad-leaved trees, open bars; deciduous broad-leaved trees, grey bars; evergreen needle-leaved trees, hatched bars; deciduous needle-leaved trees, crosshatched bars; understorey herbs, black bars).

case' scenario this pattern is essentially the same though less pronounced due to the simulated impact winter event being confined to the tropics.

Subsequent decadal averages show the global terrestrial biomass carbon pool increase (Fig. 1b) was driven by an expansion and return to dominance of the evergreen and deciduous broad-leaved forests (Fig. 2b,c). Each of the remaining functional types showed rather conserved changes with respect to pre-impact values of carbon storage. After an initial loss of vegetation carbon due to the simulated effects of wildfire, evergreen and deciduous broad-leaved forests become re-established as the dominant functional type at any given site through competitive succession simulated by the DGVM. Establishment of early Tertiary forests then allowed gradual accumulation of carbon into trunk biomass, as a result of their longevity and the CO_2-related stimulation of NPP.

To investigate the spatial pattern of ecosystem responses we computed latitudinally averaged transects of NPP and vegetation biomass 1 year and 50 years after the impact event (Fig. 3). One year after the K/T impact, NPP was suppressed by the reductions in temperature and irradiance in both scenarios, particularly near the equator and throughout the high latitudes of the northern and southern hemispheres (Fig. 3a). This pattern is reflected by the changes in latitudinal averages of vegetation carbon storage (Fig. 3b). With the less extensive effects of cooling and reduced irradiance in the 'best-case' scenario, vegetation biomass recovers more quickly to pre-impact levels (Fig. 3b).

Fifty years after the K/T impact event, the latitudinal gradients indicate NPP at low latitudes exceeds the pre-impact latest Cretaceous situation, but remains depressed in the high latitudes (Fig. 3c). Analyzed on a site-by-site basis, the change in annual NPP under conditions of global cooling and reduced irradiance, but high CO_2, shows a clear relationship with MATs between 5 and 20°C that reflects environmental effects on the functioning of Rubisco (Fig. 4). A key effect of high CO_2 is the competitive inhibition of the oxygenation reaction of Rubisco, and hence reduction in photorespiratory CO_2 evolution [32]. Since photorespiration increases markedly with temperature, which alters the solubility of CO_2 relative to O_2 and the specificity of Rubisco for CO_2 [33], its suppression allows photosynthesis to increase proportionally as temperatures increase as in the

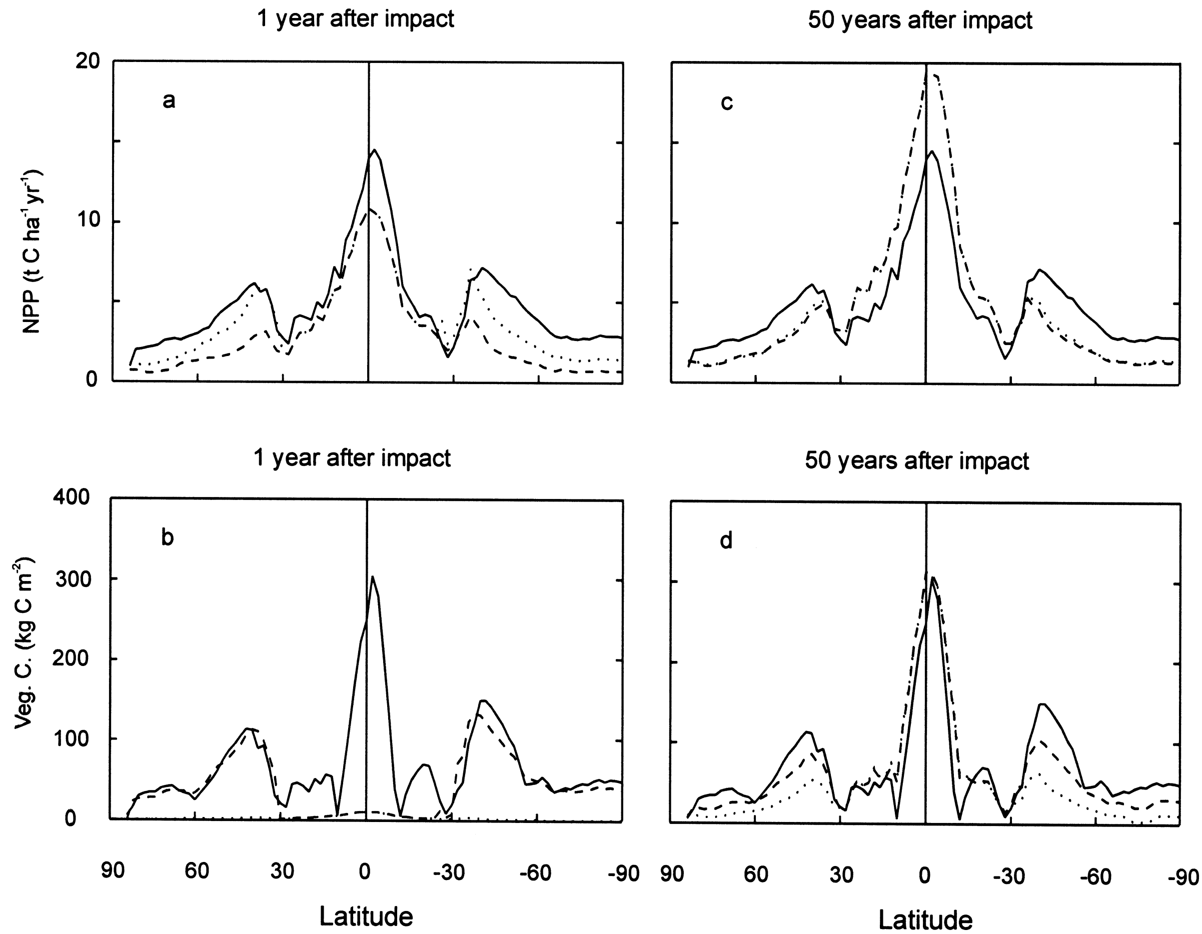

Fig. 3. Latitudinally averaged values of NPP (a, c) and vegetation biomass (Veg. C) (b, d) 1 and 50 years after the K/T impact for the 'worst-case' (dashed line) and 'best-case' (dotted line) simulations. The pre-impact (latest Cretaceous) situation is depicted by the solid lines.

tropics (Fig. 3). At low temperatures (i.e. at high latitudes) this effect is not evident and so NPP is suppressed by reduced irradiance available for photosynthesis. These climate-related effects on annual NPP, in turn, feed through to influence biomass changes in the early Tertiary forests leading to similar latitudinal gradients (Fig. 3d).

Our simulations show that global change associated with a K/T impact event had a diminished effect on the productivity and biomass of vegetation in the high latitudes but had the strongest effects occurring on vegetation in the warm, tropical, low latitudes. These results can be regarded to be relatively robust since they are not substantially altered by the imposition of either 'best-case' or 'worst-case' year zero scenarios. Moreover, they are consistent with ecological extinction gradients derived from terrestrial palaeobotanical data, which show that extinction (as indicated by mega- and macrofossils) was highest in tropical to subtropical low latitude vegetation [13,14] and lowest in higher southern latitudes [15–18].

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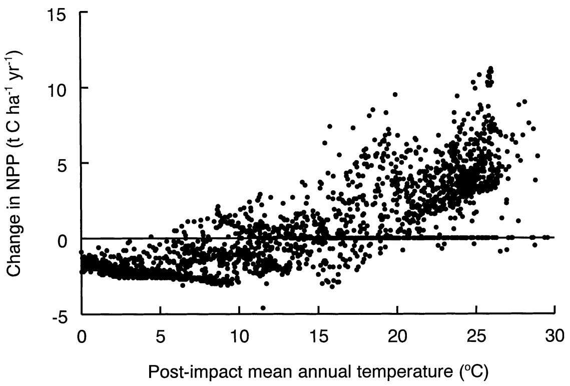

Fig. 4. Change in NPP on a site-by-site basis relative to pre-impact values 50 years after the K/T impact in relation to mean annual temperature. All results are from the 'worst-case' simulation.

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