Reevaluating the impact cratering kill curve

The global environmental effects of the Chicxulub impact event and the subsequent Cretaceous–Tertiary (K/T) boundary mass extinction event have altered our view of how life evolved. Impact cratering appears to be a geologic force that can dramatically change the fabric of life, extinguishing vast numbers of species, while opening niches for opportunistic survivors and creating completely new ecosystems out of a ravaged planet. The singular event represented by the Chicxulub impact and K/T boundary mass extinction has led to the general hypothesis that impact cratering is responsible for all mass extinction events or at least the big five of the Phanerozoic. This concept was explored by Raup (1992) who developed the "kill curve" and "extinction-impact curve" to represent the commingling of impact and evolutionary processes, which Ward (1996) suggested was the most important concept born from the K/T boundary debates.

The kill curve reflects Raup's observation that large extinction events occur less frequently than smaller events, so the percentage of species killed in any particular event increases as a function of the mean waiting time between occurrences of that size event. The extinction-impact curve marries the kill curve to a curve that reflects another observation: large impact events occur less frequently than smaller impact events. For example, while a Chicxulub-size event, producing an ~180 km diameter crater, may occur on average once per $10^8$ years, a small Meteor Crater event, producing an ~1 km diameter crater, may occur on average once per $10^3$–$10^4$ years. The combination of these two independent observations produced a relationship between the number of species extinguished and the size of impact craters (Fig. 1a), which I will call the impact cratering kill curve. Implicit in this curve is the assumption that impacts of a given size always have the same extinction effect and that larger impacts always produce greater extinctions. This has been a very useful way to envision the relationship and is reflected in studies that describe the physical and chemical effects of impact cratering events as a function of their size (e.g., Toon et al., 1997).

AMBIENT ENVIRONMENTAL CONDITIONS

However, ambient environmental conditions mediate impact-generated environmental changes and, thus, their biological consequences, effects that Raup (1992) and Ward (1996) recognized in a general form, and which were recently explored in more detail (Kring, 2002a,b). For example, while the injection of greenhouse-warming CO$_2$ into the atmosphere by the Chicxulub impact may have caused global mean temperatures to rise 1.5 to as much as 7.5 °C (Pierazzo et al., 1998; Beerling et al., 2002), a similar event in the Archean, which already had a CO$_2$-rich atmosphere, would have had little effect on temperatures. Likewise, while the Chicxulub impact event generated additional atmospheric CO$_2$ by igniting wildfires (Kring and Durda, 2001, 2002), such an effect could not have been produced prior to the evolution of land plants in the Ordovician or early Silurian.

EXTANT LIFE AND ECOSYSTEMS

The biological consequences of impact-generated environmental effects are also a function of the types of organisms and ecosystems extant at the time of an impact. It seems clear that an impact's effect on a microbial world would be much different than on a modern world. Similarly, an impact's effect when most of the biomass was in subsurface ecosystems
would be much different than that produced by an impact today when large fractions of the biomass are in marine, forest, and grassland ecosystems that are more susceptible to atmosphere-mitigated perturbations like enhanced opacity and acid rain. Consequently, an impact event that occurred in the earliest Archean, when the world was dominated by non-photosynthetic archaean and bacteria, would not be affected by impact debris blocking sunlight and the toppling of photosynthetic-based food chains like that produced by the Chicxulub impact event.

**CONSEQUENCES FOR THE KILL CURVE**

These caveats suggest the impact cratering kill curve (Fig. 1a) is too simple. It is more likely there are a family of curves, each one reflecting ambient environmental conditions and extant ecosystems at specific times in Earth history (Fig. 1b). It is also likely that the effects of an impact event must overwhelm critical thresholds, above which a group of species cannot survive, either because they cannot adapt, migrate, or remain dormant long enough to survive. This implies the series of curves may have a more complicated stepped-structure (Fig. 1c).

This may be an uncomfortable result, because it implies the outcome of an impact event of a particular crater-forming size is less predictable. Nonetheless, the result also provides direction for future studies: to determine environmental and biological thresholds, to measure the environmental and biological consequences of known impact events (e.g., Manicouagan, Popigai), to determine the mitigating or catalyzing effects of ambient conditions, and model the environmental effects of impact events farther back in time. This also affects the way in which we assess the hazards of future impacts. Models or impact-cratering kill curves based on the Chicxulub impact event and other late Phanerozoic events will be better proxies for modern hazards than those for Archean, Proterozoic, and early Phanerozoic impact events, because they better reflect the structure of life now.


David A. Kring
Lunar and Planetary Laboratory
University of Arizona
Tucson, Arizona 85721, USA

**REFERENCES**

BEERLING D. J., LOMAX B. H., ROYER D. L., UPCHURCH G. R., JR.


