Science & Society

Deep impact: the rising toll of fishing in the deep sea

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The deep ocean is one of the last great wildernesses. Waters deeper than 1000 m cover an estimated 62% of the planet. In spite of more than 150 years of exploration, the ocean depths remain virtually unknown. Biological science has so far touched upon only one millionth of the deep-sea floor, but new technology is revealing unknown and exotic habitats as quickly as we look. Those technologies are also bringing the deep within reach of industry, with devastating consequences.

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Cast a dredge over the side of a ship far out to sea and the chances are that you will raise a bucket full of mud and worms. Sediment blankets much of the deep-ocean floor [1] and was a source of endless tedium for those lowering dredges and raising mud during the three-year voyage of *HMS Challenger* in the 1870s. This voyage marked the first systematic look at the biology of the deep sea. Perhaps all that mud contributed to the suicide, two cases of insanity and 61 desertions that are among its lesser known achievements [2].

Dredges are still a mainstay of deep-sea biology, but today they are supplemented by a burgeoning array of sophisticated technology. Remotely operated vehicles, video, bottom landers, submarines and sonar now provide windows on the deep that are forcing us to rethink our notions of life there. In the past few decades, we have discovered remarkable new habitats – spectacular hydrothermal vents, cold seeps, gas hydrates and cold-water coral reefs [3]. A closer look at seamounts and canyons reveals them to be hotspots of production that harbour diverse faunas that are rich in unique species.

However, scientists are not the only ones taking an interest in the deep. These waters offer the prospect of lavish rewards to mining, oil and gas exploitation, and fishing concerns. In a new report prepared for the World Wide Fund for Nature (WWF) and World Conservation Union (IUCN), scientists from the Southampton Oceanography Centre and an expert on international law present a primer in deep-sea biology and explore current and potential threats to deep water and high-seas life [3]. Although deep-ocean mining still lies in the future, fishing is already causing great concern.

Fishing deeper

Deep-water fisheries began in the 1960s and 1970s, coinciding with declines in shallow-water stocks that stimulated the development of new and more robust fishing gear [4]. Larger vessels, more powerful winches, stronger cables and rockhopper trawls expanded greatly the reach of fishing. The move to deep water is being encouraged further by governments offering grants and subsidies [5] in efforts to alleviate hardship brought about by the collapse of shallow-water fish stocks caused by overfishing. Consequently, there has been a worldwide scramble to exploit these resources and 40% of the world's trawling grounds are now in waters deeper than the continental shelves [6].

Early rewards from deep-sea fishing can be great. For example, the orange roughy *Hoplostethus atlanticus* fishery began in the 1970s. It took off in the 1980s when spawning aggregations were discovered around deep seamounts off New Zealand and southern Australia. Catches from these aggregations could be incredible, sometimes 60 t from a 20-min trawl (J.A. Koslow, pers. commun.). However, in just over a decade, stocks collapsed to <20% of their pre-exploitation abundance, largely through sequential depletion of aggregations [4,7]. In the North Atlantic, populations have met with a similar fate. Here, the mainly French fishery peaked at 4500 t during its first two years, then dropped to 1000 t three years later [5].

Other fisheries have also flourished briefly then diminished. For example, pelagic armourhead *Pseudopentaceros wheeleri* were fished over seamounts in international waters northwest of Hawaii from the late-1960s to mid-1970s. In 1976, 30 000 t were landed but, the year after, catches collapsed to just 3500 t and have never recovered [8]. In the North Atlantic, blue ling *Molva dipterygia* fisheries also rely on spawning aggregations. As new areas are rapidly depleted, the survival of the fishery depends upon the continuing discovery of unexploited aggregations [9].

We know from shallow waters that unregulated or poorly controlled fishing of aggregations is a quick ticket to fishery collapse [10]. For example, throughout the Caribbean, Nassau grouper *Epinephelus striatus* spawning aggregations numbering tens of thousands of fish were eliminated in just a few years, never to reform [11]. Spawning aggregations concentrate fish from a very large area into a very small one. For example, orange roughy travel hundreds of kilometres to spawn over seamounts in the Southern Hemisphere [12]. Aggregations can also form in other ways. Adult pelagic armourhead, for example, migrate to seamounts from broad areas of the northern Pacific, and live out the rest of their lives there [13]. Where fishing effort is difficult to control, as it is on the high seas, exploiting dense aggregations can be closer to mining than to fishing, because depletion is rapid and recovery unlikely [10].

Deep-water fisheries fail the sustainability test on another ground. The almost glacial pace of life in the deep makes it a particularly unsuitable place to fish. Many species grow slowly and live to extraordinary ages. For example, new radiometric aging methods reveal that rockfish *Sebastes* spp. longevity increases exponentially with the deepest occurrence of a species (Fig. 1), and some species can reach 200 years old [14]. Cailliet *et al.* [14] suggest that great longevity could be facilitated by slow metabolism. In deep-sea fish, metabolic rates are typically an order of magnitude lower than in fish living near the surface [15]. However, this is not the only factor – some species dwelling on seamounts have metabolic rates similar to those of species living at the surface yet still live to a great age, perhaps because of low rates of predation [15].

Long lifespan is usually paired with late reproduction. Icelandic roundnose grenadier *Coryphaenoides rupestris* can live to their 70s and mature at ~14–16 years old [16]. Orange roughy, which reach

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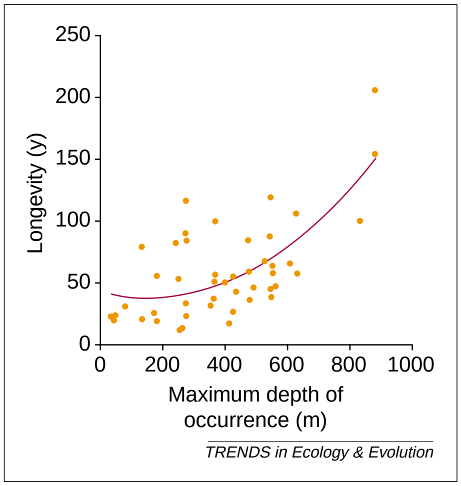

Fig. 1. Deep-sea fish generally live longer than do those in shallow water. The longevity of rockfish species from the genus *Sebastes* (Pisces: Scorpaenidae) increases exponentially with their deepest depth of occurrence. ($r^2 = 0.51$.) Redrawn, with permission, from [14].

150 years old, do not mature until their mid-20s to mid-30s [17]. For shallow-water fish, a large body size and advanced age at maturity are two of the most reliable predictors of vulnerability to overexploitation [18]. Long life, late maturity and high fecundity are also indicators of sporadic recruitment success [18]. The life-history characteristics of deep-sea species place them at the extreme end of the vulnerability spectrum. What these characteristics point to is that deep-water fisheries are repeating the process of sequential stock depletion that has been the hallmark of shallow-water fisheries [19]. The difference is that depletion is more rapid, and recovery will be much slower and even less certain than in shallow water.

The collateral costs of deep-water exploitation

Deep-sea fisheries are inflicting terrible collateral damage. Only a handful of species is marketable, largely because most have soft, watery flesh that is undesirable to consumers and of little use for fishmeal [5]. Most species are discarded as bycatch – bykill really, because there is 100% mortality of fish brought up from great depths [20]. Furthermore, most deep-sea species are adapted to conditions of low turbulence. They have large scales, weak skins and lack the well-developed mucus coating of shallow water fish [21]. Fish that enter trawls are rapidly stripped of their scales and skin, so that even small fish that pass through trawl meshes probably suffer heavy mortality.

Fisheries are concentrated into areas with some of the greatest biological significance in the deep sea. Seamounts, together with steep slopes, such as those of canyon walls, are among the few deep-sea habitats where currents are strong enough to prevent sediment accumulation. The same currents also bring food, and a rich benthic fauna of suspension feeders develops as a result, including corals, sponges, seafans and hydroids. This constant input of food supplies the large fish aggregations that have attracted fishers. Koslow *et al.* [22] found 300 species of fish and invertebrates inhabiting Tasmanian seamounts. But many of these seamounts have literally been stripped bare by trawling. For example, there was 95% bare rock on fished peaks compared with just 10% on unfished ones [22], and, on average, unfished seamounts had double the benthic biomass and 46% more species than did fished areas.

The closer we look at the deep sea the more we challenge our previous ideas. De Forges *et al.* [23] reported >850 macro- and megafaunal species from seamounts of the southwestern Pacific. This is striking when you consider that only 597 invertebrate species had been recorded from seamounts between the *HMS Challenger* expedition of the 1870s and 1987. The new samples reveal hitherto unsuspected levels of endemism. Between 29% and 34% of the species collected were potential seamount endemics and new to science [23]. Many species, it seems, have extremely limited geographical distributions and are restricted to closely spaced ranges of underwater peaks. The potential for trawl damage to cause extinctions is high [24].

Other habitats are being caught in the fishing crossfire. It is only in the past five years that the extent of coldwater coral reefs in the North Sea has been appreciated, although they were first described over a century ago [25]. This habitat occurs at depths of 100–2000 m and is built largely by a single species of coral *Lophelia pertusa*. Growing at rates of just a few millimetres a year, over millennia the corals have created reef-like mounds that can reach up to 200 m high and 4000 m long [26]. Off the Norwegian coast, oil companies exploring the seafloor with remotely operated video cameras came across a region of reefs that extend for 13 km [27]. *Lophelia* beds support a rich assemblage of species (Fig. 2), totalling >800 at the last count [28]. Evidence from

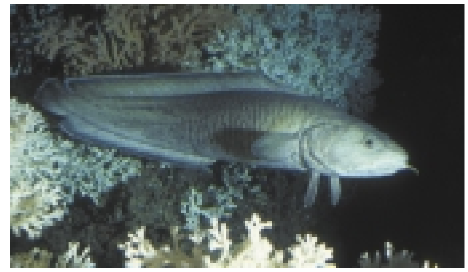

Fig. 2. *Lophelia* reef habitat at 273 m on the Sula Ridge, Norway, showing a cusk fish *Brosme brosme*. Photograph reproduced, with permission, from Andre Freiwald, University of Tübingen.

video suggests that they also form important nursery grounds for many fish species.

Video and photographic surveys reveal troubling evidence of the vulnerability of this fragile habitat to fishing, including deep parallel grooves of pulverized coral ploughed by trawl doors [29]. These doors keep the net open and the trawl on the bottom, and deeper trawling and rougher seabeds require heavier doors, which can weigh 2–5 t each. Norwegian fishers have long known of the presence of *Lophelia* reefs and developed fishing techniques to reduce net damage and increase catches (although only over the short term), such as dragging chains across the bottom ahead of trawls to mow down obstructions. At a recent symposium on deep-water corals, Norwegian scientists estimated that up to half of these reefs have already been damaged or destroyed by fishing (Fossa *et al.* 2000; http://home.istar.ca/~eac_hfx/symposium/).

Across the Atlantic, there are similar problems. To people fishing off Nova Scotia, glass sponges are a nuisance. In newly fished areas, they clog nets with literally tonnes of material akin to fibreglass. Over time, the problem diminishes as nets clear the bottom of its biota. This process of seabed habitat transformation has been underway since the early days of trawling. In the 19th and early 20th centuries, fishers used to regularly trawl up giant gorgonians [30]. Radioisotope aging of smaller colonies put them at hundreds of years old, suggesting ages of 2000 or more for the largest specimens [30].

There are fishing methods that are less destructive to deep-water habitats, including long-lines, traps and gill nets. However, the use of gill nets is still problematic, because lost nets can continue fishing for very long periods. In shallow water, the fishing power of lost nets is rapidly reduced by storms, tidal currents and fouling algae, but in the calm and dark of the deep, nets remain lethal for much longer. Fishing with long-lines does less damage to habitats and there is less wasted bycatch [21], but there is still no way out of the problem of extremely low rates of production. For example, the sustainable annual take of orange roughy in the southern ocean has been estimated at only 1.5% of the unfished biomass [31]. Given the high costs of deep-sea fishing (specialist gear, larger boats and long voyages) it seems likely that it can be profitable only if pursued in the present mode of serial depletion. There is probably no such thing as an economically viable deep-water fishery that is also sustainable. It is clear that the biology of deep-sea organisms compels us to rethink attitudes to exploitation that we have developed from experience with organisms living in the 'fast-lane' of shallow seas. Merrett and Haedrich [32] argue that we must consider deep-sea fish stocks as nonrenewable resources.

Deep-sea ecosystems need urgent protection

The clear cutting of old-growth redwood forests in the western USA during the 19th century spurred the creation of the first national parks. The analogy is obvious. Ancient groves of invertebrates are being clearcut by trawling just as quickly and surely as loggers felled groves of giant redwoods [33]. The unique megafauna of these hidden aquatic glades is being hooked and netted faster than they can possibly be replaced. As with rainforests, we are probably losing species far more quickly than we can describe them. We urgently need to extend protection to large areas of the deep sea.

Most deep-sea fishing is unregulated [3], but no licensing, quota scheme or effort control will save deep-ocean life, because it can be depleted or destroyed much too rapidly for these mechanisms to work. The answer is to create marine reserves that are entirely off limits to fishing. Norway moved fast to protect its coldwater coral reefs from trawling in 1999, soon after their extent and vulnerability became known. To date, no other country has done so. In Australia, twelve seamounts have been protected from bottom fishing within the 370 km^2 Tasmanian Seamounts Marine Reserve (Dahl-Tacconi, 2000; http://home.istar.ca/~eac_hfx/symposium/), New Zealand has protected 19 seamounts and the USA has created a small marine-protected area encompassing two seamounts off Alaska [34]. However, none is protected from fishing all the way to the surface. It is still unclear how closely linked benthic and pelagic foodwebs are around seamounts. For example, vertical migrations of organisms transfer nutrients from shallow water to bottom habitats. This, together with the nutrient 'snowfall' from animals aggregated higher in the water column helps explain why seamount assemblages are so rich [15]. Consequently, partial protection measures might not assure the long-term wellbeing of bottom-living communities [20,35]. Surface to bottom protection from fishing offers more security but could be more difficult to implement due to greater fishing industry opposition [36].

National initiatives represent a crucial first step for deep-sea conservation, but much of the deep lies beyond national jurisdiction. Fifty percent of the planet comprises high seas [3], which are outside the 200-mile national limits. High-seas regulation poses great challenges [37], but as the new WWF–IUCN report shows, present international laws provide a framework for creating high-seas marine reserves [3]. Unfortunately, the present rate of expansion of deep-sea fisheries gives us little time to act. Unless we work quickly to establish reserves, we might realize the Victorian vision of a deep sea that is devoid of larger life – the kingdom-of-the-worms once more.

Acknowledgements

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References

1 Gage, J.D. and Tyler, P.A. (1991) *Deep-sea Biology – A Natural History of Organisms at the Deep-sea Floor*, Cambridge University Press
2 Broad, W.J. (1997) *The Universe Below*, Simon and Schuster
3 WWF/IUCN (2001) *The Status of Natural Resources on the High-seas*, World Wide Fund for Nature and World Conservation Union
4 Koslow, J.A. *et al.* (2000) Continental slope and deep-sea fisheries: implications for a fragile ecosystem. *ICES J. Mar. Sci.* 57, 548–557
5 Donnelly, C. (1999) *Exploitation and Management of the Deep Water Fisheries to the West of Scotland*, Marine Conservation Society
6 McAllister, D.E. *et al.* (1999) *A Global Trawling Ground Survey*, Marine Conservation Biology Institute, World Resources Institute and Ocean Voice International
7 Clark, M. (1999) Fisheries for orange roughy (*Hoplostethus atlanticus*) on seamounts in New Zealand. *Ocean Acta* 22, 593–602
8 Sasaki, T. (1986) Development and present status of Japanese trawl fisheries in the vicinity of seamounts. In *The Environment and Researches of Seamounts in the North Pacific. Proceedings of the Workshop on the Environment and Resources of Seamounts in the North Pacific* (Uchida, R.N. *et al.*, eds), pp. 21–30, US Dept of Commerce, NOAA Technical Report NMFS 43
9 Gordon, J.D.M. *et al.* (1999) *Deep-water Fish and Fisheries Project*, Report of the Dunstaffnage Marine Laboratory
10 Johannes, R.E. (1998) The case for data-less marine resource management: examples from tropical nearshore fin fisheries. *Trends Ecol. Evol.* 13, 243–246
11 Sadovy, Y. (1993) The Nassau grouper, endangered or just unlucky? *Reef Encount.* 13, 10–12
12 Francis, R.I.C.C. and Clark, M.R. (1998) Inferring spawning migrations of orange roughy (*Hoplostethus atlanticus*) from spawning ogives. *Mar. Freshw. Res.* 49, 103–108
13 Martin, A.P. *et al.* (1992) Population genetic-structure of the armorhead, *Pseudopentaceros wheeleri*, in the North Pacific Ocean – application of polymerase chain reaction to fisheries problems. *Can. J. Fish. Aquat. Sci.* 49, 2386–2391
14 Cailliet, G.M. *et al.* (2001) Age determination and validation studies of marine fishes: do deep-dwellers live longer? *Exp. Gerontol.* 36, 739–764
15 Koslow, J.A. (1997) Seamounts and the ecology of deep-sea fisheries. *Am. Sci.* 85, 168–176
16 Bergstad, O.A. (1990) Distribution, population structure, growth and reproduction of the roundnose grenadier (*Coryphaenoides rupestris*) (Pisces: Macrouridae) in the deep waters of the Skagerrak. *Mar. Biol.* 107, 25–39
17 Horn, P.L. *et al.* (1998) Between-area differences in age and length at first maturity of the orange roughy *Hoplostethus atlanticus*. *Mar. Biol.* 132, 187–194
18 Jennings, S. *et al.* (1998) Life history correlates of responses to fisheries exploitation. *Proc. R. Soc. London B Biol. Sci.* 265, 333–339
19 Roberts, C.M. (2000) Why does fishery management so often fail? In *Science and Environmental Decision Making* (Huxham, M. and Sumner, D., eds), pp. 170–192, Prentice Hall
20 Gordon, J.D.M. (2001) Deep-water fisheries at the Atlantic Frontier. *Cont. Shelf Res.* 21, 987–1003
21 Connolly, P.L. and Kelly, C.J. (1996) Catch and discards from experimental trawl and longline fishing in the deep water of the Rockall Trough. *J. Fish. Biol.* 49, 132–144
22 Koslow, J.A. *et al.* (2001) Seamount benthic macrofauna off southern Tasmania: community structure and impacts of trawling. *Mar. Ecol. Progr. Ser.* 213, 111–125
23 De Forges, B.R. *et al.* (2000) Diversity and endemism of the benthic seamount fauna in the southwest Pacific. *Nature* 405, 944–947
24 Roberts, C.M. and Hawkins, J.P. (1999) Extinction risk in the sea. *Trends Ecol. Evol.* 14, 241–246

25 Roberts, M.J. (1997) Coral in deep water. *New Sci.* 155, 40–43
26 Rogers, A.D. (1999) The biology of *Lophelia pertusa* (Linnaeus 1758) and other deep-water reef-forming corals and impacts from human activities. *Int. Rev. Hydrobiol.* 84, 315–406
27 Freiwald, A. *et al.* (1999) Grounding Pleistocene icebergs shape recent deep-water coral reefs. *Sediment. Geol.* 125, 1–8
28 Duncan, C. and Roberts, J.M. (2001) Darwin mounds: deep-sea biodiversity 'hotspots'. *Mar. Conserv.* 5, 12–13
29 Roberts, M.J. *et al.* (2000) Seabed photography, environmental assessment and evidence for deep-water trawling on the continental margin west of the Hebrides. *Hydrobiologia* 441, 173–183
30 Risk, M.J. *et al.* (1998) Conservation of cold and warm water seafans: threatened ancient gorgonian groves. *Ocean Voice Int. Sea Wind* 12, 2–21
31 Clark, M. (2001) Are deepwater fisheries sustainable? The example of orange roughy (*Hoplostethus atlanticus*) in New Zealand. *Fish. Res.* 51, 123–135
32 Merrett, N.R. and Haedrich, R.L. (1997) *Deep-sea Demersal Fish and Fisheries*, Chapman & Hall
33 Watling, L. and Norse, E.A. (1998) Disturbance of the sea bed by mobile fishing gear: a comparison to forest clearcutting. *Conserv. Biol.* 12, 1180–1197
34 Wing, K. (2001) *Keeping Oceans Wild. How Marine Reserves Protect Our Living Seas*, Natural Resources Defense Council
35 Probert, P.K. (1999) Seamounts, sanctuaries and sustainability: moving towards deep-sea conservation. *Aquat. Conserv.* 9, 601–605
36 Roberts, C.M. and Hawkins, J.P. (2000) *Fully Protected Marine Reserves: A Guide*, WWF Endangered Seas Campaign and University of York
37 Hyrenbach, K.D. *et al.* (2000) Marine protected areas and ocean basin management. *Aquat. Conserv.* 10, 437–458

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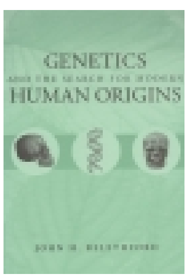
Book Review

The triumphant trellis (and the transubstantiation of modern humans)

Genetics and the Search for Modern Human Origins
by J.H. Relethford. John Wiley and Sons, 2001. £53.95 hbk. (252 pages)
ISBN 0 471 38413 5



Could human evolution possibly become more complicated than it already is? This feeling overwhelms me each time I read a paper, by a proponent of multiregionalism, that hinges on recurrent gene flow over a vast geographical expanse of physical distance for an immense duration of time acting on unknown aspects of behavior, morphology and physiology. As a geneticist, I believe that the main answer to 'What makes us human?' will come from analysis of expression arrays that compare gene loci from human chromosome regions 2p and 2q with homologous loci on chimpanzee chromosomes 12 and 13. But will this provide the complete answer? To paraphrase John Maynard Smith, my 30 years as a geneticist, and 20 years as a physical anthropologist have convinced me that the problems in understanding human evolution are not in genetics or fossils, but in how to fit them together.

This book purportedly shares this mind set. Although Relethford states his sympathies for the objective evaluation of new evidence, his main aim is to show that there is weak genetic support for a recent African origin for all modern humans, and that multiregionalism is alive and well, rescued by our ignorance of how fast and how far people moved when they did expand out of Africa. His goal is to convince the reader that phylogenetic analysis of sequence or haplotype diversity is an inappropriate way to portray the genetic population structure of interbreeding groups.

Relethford confesses that he was swayed, at first, by the evidence from multiple genetic loci indicating that an effective population size of ~10 000 individuals could not have remained in migrational equilibrium for 1.7 million years over five continents. However, he has since changed his mind and now envisions that migration pulses of 25–50 people every 40–125 generations could probably explain current diversity patterns. Local demes nearly went extinct and were swamped occasionally by adjacent immigrant peoples, somehow related to the original occupants. That sort of model requires the use of the 'r' word, and I do not mean rare alleles. His sympathies are apparent when he writes of his distaste for dogmatic statements made by molecular geneticists. This left me wondering about how many paleoanthropology news conferences he has attended.

He covers topics such as head shapes in Irish counties, ecological estimates of carrying capacity for hunter–gatherers, age structure, Wright's statistics, and genetic diversity estimates. The strong points are the chapters on population size and the search for common ancestors. The weakest include Relethford's equation of simulation for rigorous mathematical modelling, a failure to discuss assumptions of coalescent theory, and his summary of important ancient DNA analyses. William Boyd rightly stated, in 1950, that, if we go back only 500 years, we arrive at a time when there must have been many of our ancestors from whom we cannot have inherited even so much as a single gene [1].

According to Relethford, mtDNA and Y models of population replacement based on phylogenetic analysis are inconsistent with the total evidence. However, a model that he favors, based on larger ancestral populations in Africa and a migration matrix favoring immigration into Asia, clearly predicts that 2400 (20%) of the 12 000 typed Asian Ys [2] should be identifiable distinctly as old and Asian, unless selection (natural or sexual?) has eliminated them completely from current populations. In my mind, the answer to what made us modern humans must wait for a technology to analyse DNA remaining in bones that are older than the current 100 000-year ceiling. No amount of simulation will replace bands on gels and fossils in hand.

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References

1 Boyd, W.C. (1950) *Genetics and the Races of Man*, D.C. Heath
2 Ke, Y. *et al.* (2001) African origin of modern humans in East Asia: a tale of 12,000 Y chromosomes. *Science* 292, 1151–1153

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