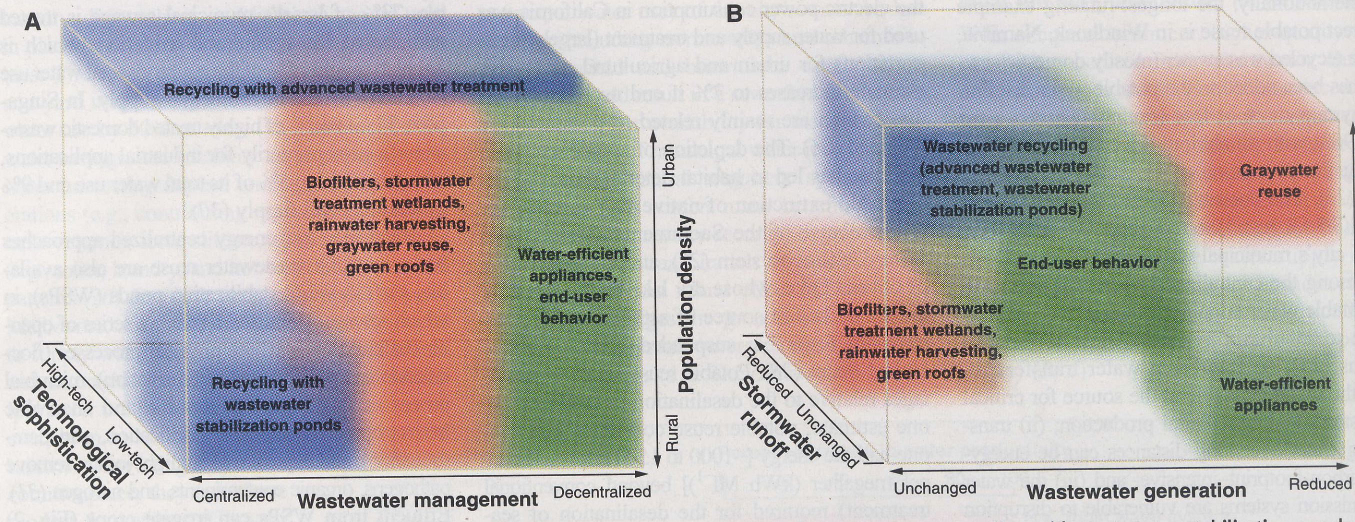

Fig. 3. Wastewater reuse and water-saving schemes discussed in the text, arrayed relative to a few key attributes (**A**) and performance indicators (**B**). The color scheme matches that in Fig. 1; substituting, red; regenerating, blue; and reducing, green. Certain schemes can be classified in more than one way; for example, wastewater recycling with wastewater stabilization ponds be considered blue or red, depending on the end use and what water is substituted or regenerated. The adoption of water-saving schemes is enced by policy, law, regulations, markets, and incentives.

of Melbourne's municipal supply, and uses approximately 500 kWh Ml^{-1} less energy than conventional wastewater treatment (*32*). Recycled water from the Western Treatment Plant is used for a variety of nonpotable applications, including in-plant uses and dual pipe schemes for the irrigation of agricultural crops, gardens, golf courses, and conservation areas.

Primary concerns associated with wastewater reuse include the buildup of contaminants and salts in soils (in the case of wastewater irrigation) and the possibility that incomplete removal of chemical or microbiological hazards during treatment may cause disease in an exposed population (*6*). Disease risk can be evaluated on a case-by-case basis using a statistical framework, such as quantitative microbial risk assessment, that predicts a population's disease burden, given the types and concentrations of pathogens that are likely to be present in the water, as well as particular exposure scenarios (*33*).

What Are the Opportunities for Reduction?

Water productivity can also be improved by reducing the volume of water used to produce a fixed value of goods and services. A modeling study of the water supply system in Florianopolis, Brazil, concluded that replacing single-flush toilets with dual-flush toilets would reduce municipal water use in the city by 14 to 28% and reduce energy use at upstream (drinking water) and downstream (wastewater) treatment plants by 4 GWh $year^{-1}$—enough energy to supply 1000 additional households (*34*). An analysis of 96 owner-occupied single-family homes in California, Washington, and Florida concluded that the installation of high-efficiency showerheads, toilets, and clothes washers reduced household use of municipal water by 10.9, 13.3, and 14.5%, respectively (*35*). Because water is not technically required for bathroom waste disposal, the installation of composting toilets and waterless urinals can reduce municipal water use even further (*36*).

Agriculture accounts for the majority of global freshwater withdrawals (*37*), and thus even small improvements in water productivity in this sector can result in substantial water savings. Water savings can be achieved by switching to less–water-consuming crops, laser-leveling of fields, reducing nonproductive evaporation of water from soil or supply canals, changing irrigation scheduling, and adopting more efficient sprinkler systems, including microirrigation techniques (drip irrigation and microsprinklers) that precisely deliver water to plant roots (*37*). These approaches could help mitigate escalating water demand associated with growing energy crops, such as corn, particularly if projected increases in U.S. biofuel production are realized (*38*).

Drinking water is lost after it leaves treatment plants because of physical leaks in urban water distribution systems and poor accounting. Worldwide, the total volume of this "nonrevenue water" is estimated to be 49 Tl per year (*39*). Pipeline losses range from over 50% in much of the developing world to less than 10% in well-run utilities (*39*). The World Bank estimates that if just half of the losses in developing countries were eliminated, $1.6 billion would be saved annually in production and pumping costs, and drinking water could be extended to an additional 90 million people without the need for new treatment facilities (*39*).

What Is the Role of Water Quality?

Protection of water quality is also a priority. The Catskill Mountains supply drinking water for New York City. When agriculture and residential developments threatened surface-water ity, the city considered building an $8 billion treatment plant, but instead opted to spe billion buying land and restoring habitat water supply catchment. This approach ob the need for a treatment plant, saved the c lions of dollars in capital and ongoing ope and maintenance costs, and preserved a ecosystem (*40*).

What Is the Right Mix of Wastewater Reuse and Water-Saving Schemes?

The wastewater reuse and water-saving sc described above are each tailored to a par scale of implementation (from single ho entire countries), population density (from to rural), and level of technological sophist (from high-tech to low-tech) (Fig. 3A). substitution schemes using advanced wast treatment may be feasible in an urban c but not in a rural context. Furthermore, no scheme simultaneously maximizes wastew use, minimizes wastewater generation, an imizes stormwater runoff (Fig. 3B). How community identify the right mix of schem will optimize their water systems? One stu uated infrastructure options for a hypotheti idential development in the southeast of E and concluded that every community has nological state-of-the-art equilibrium beyon tradeoffs are required (*41*). Wastewater re water-saving schemes can improve water ergy use, and land use up to the equilibriu Beyond the equilibrium point, further red in water use require increasing either ene (if high-tech options are used) or land low-tech options are used) (*41*). Human ior should also be considered in the asses of optimal water management strategies,

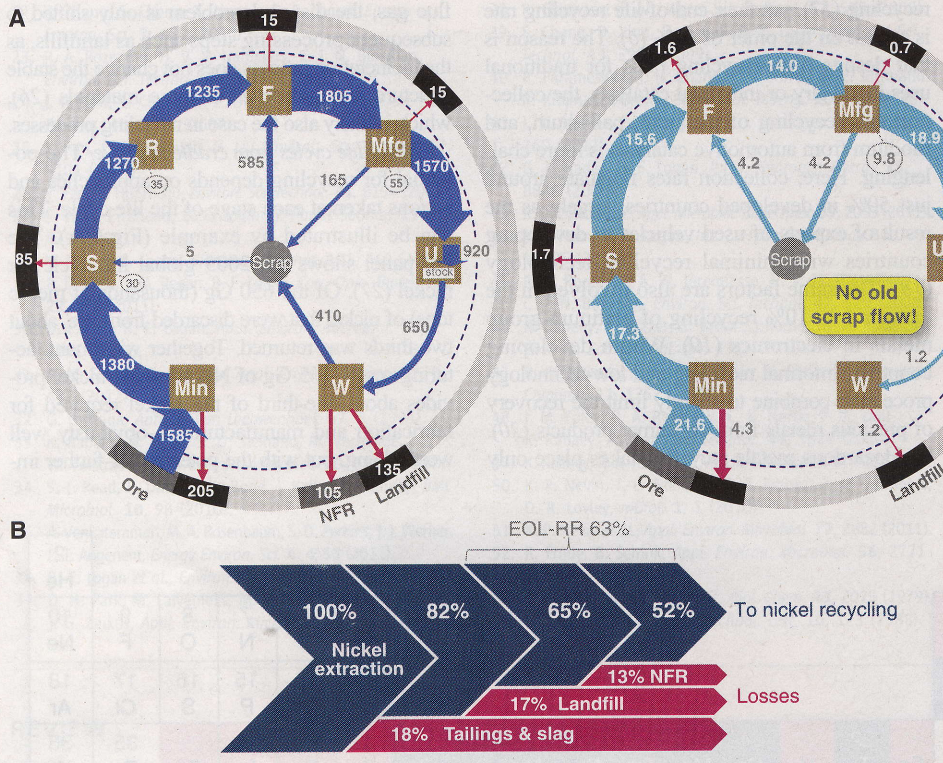

Fig. 2. **(A)** The global cycles of nickel for the year 2005 [left, adapted from (*27*)] and neodymium for 2007 [right, adapted from (*16*)]. The numbers indicate flows of metal within the anthroposphere, in Gg (thousands of metric tons). Flows crossing the dotted line transfer metal to the anthropogenic cycle or vice versa. The width of the arrows is an approximate indication of flow magnitude. Min, mining; S, smelting; R, refining; F, fabrication of semi-products (rolls, sheets, etc.); Mfg, manufacturing; W, waste management and recycling. **(B)** Material efficiencies across nickel's life cycle. Of the extracted nickel, 82% enters fabrication, manufacturing, and end use; 65% enters the recycling processes; and 52% is recycled for another use in which nickel's properties are required (functional recycling). Losses across one life cycle amount to 48%. EOL-RR, end-of-life recycling rate; NFR, nonfunctional recycling.

incorporation as a trace constituent into a recycled stream of iron or copper alloys (Fig. 2B). This confirms the results of Markov chain modeling, which shows that a unit of the common metals iron, copper, or nickel is only reused two or three times before being lost (*28*–*30*), gainsaying the notion of metals being repeatedly recyclable.

Product Recovery and Recycling Technology

An engineer or scientist instinctively thinks of technology when the topic of recycling is raised, but it turns out that social and cultural aspects are at least as important, perhaps more so (*31*, *32*). Metal price is a key driver directly affecting collection and processing efficiencies (*1*, *5*). Extensive manual disassembly of discarded electronics is typically not economically feasible in industrialized countries but may be advantageous in emerging economies such as India and China (*17*, *33*). Figure 3 shows the main steps involved in recycling, the key perspective being that the overall efficiency is the product of the efficiencies at each stage. As with a chain, the weakest link controls the performance of the system. The figure also shows the associated recovery and recycling efficiencies for nickel and neodymium across all end-of-life products, as well as the specific cases of nickel and rhenium from end-of-life aerospace superalloys. The first stage is collection, which refers to the transfer of an unwanted product from the owner to a suitable recycling facility.

Collection, pre-processing, and end processing. Collection rates vary greatly among different waste streams, depending on price, logistics, and other factors. Waste of electrical and electronic equipment (WEEE), in contrast, often has relatively low collection rates despite legislative efforts. In the European Union, 25 to 40% of WEEE is collected and treated in the official system (*34*), the rest being discarded into municipal waste, exported as used products or scrap, or otherwise lost. Current WEEE legislation in the European Union and Japan focuses on mass recovery, which favors steel and base metals used in large quantities, whereas precious and specialty metals, found in small electrical and electronic equipment, are often not recovered (*35*, *36*). Considering this situation, as well as the recent debate on critical metals [e.g., (*37*)], a revision of these priorities seems likely (*34*).

After collection, the postconsumer metal enters a series of pre-processing steps, including repeated sorting (e.g., manual, magnetic, optical), dismantling, and physical and chemical separation (*38*, *39*). Issues of scale are important here. Virgin materials processing is generally large in scale, using processes underwritten by historically low energy prices. In contrast, recycling is often local, more labor-intensive, and smaller in scale. In such a situation, the monetary returns are often not sufficient to justify the purchase of modern "sense and sort" technologies, and much otherwise recoverable material is lost.

The example of a nickel- and rhenium-containing aerospace superalloy shows how price, material combinations, size, and shape can drive the efficiency (Fig. 3). One company estimates that collection rates of these superalloys are around 90% because of their high value and the favorable logistics of a relatively small industry (*40*). Around 80% of the scrap is in solid pieces that can easily undergo grade-specific identification and recycling. The other 20% is in the form of turnings and other small fractions and can be sent to a stainless steel smelter. This translates into an 81% efficiency for nickel, which is required in both the superalloy and stainless steel, but only a 68% efficiency for rhenium (Fig. 3). Similarly, neodymium may be collected at a rate of 30% from electronics or magnets, but with no element-specific recycling technology existing at present, its overall recycling efficiency is near zero and it will either be discarded or become a trace element in recycled metal.

After pre-processing, the material will be sent to a smelter or other thermochemical facility where processing has been optimized (end-processing). In most cases, these are primary smelters, although some facilities—including electric arc furnaces in steel production as well as smelters processing electronic wastes for the recovery of precious metals, copper, and some specialty metals—specialize in processing secondary metals. As Fig. 1 shows, some metals have fairly high overall recycling rates, generally because they are used in large, easy-to-identify applications such as steel beams or lead batteries, but half or more of the metals face the larger challenge of the recycling sequence and its typical efficiencies.

Recycling technology. Collection efficiencies are related to social and governmental factors, but separation and sorting efficiencies relate to