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An Assessment of Aquifer Water Quality

U.S. Geological Survey

Foreword

The United States has made major investments in assessing, managing, regulating, and conserving natural resources, such as water and a variety of ecosystems. Sustaining the quality of the Nation's water resources and the health of our diverse ecosystems depends on the availability of sound water-resources data and information to develop effective, science-based policies. Effective management of water resources also brings more certainty and efficiency to important economic sectors. Taken together, these actions lead to immediate and long-term economic, social, and environmental benefits that make a difference to the lives of millions of people.

Two decades ago, Congress established the U.S. Geological Survey's National Water-Quality Assessment (NAWQA) Program to meet this need. Since then NAWQA has served as a primary source of nationally consistent information on the quality of the Nation's streams and groundwater, on ways in which water quality changes over time, and on the natural features and human activities affecting the quality of streams and groundwater. Objective and reliable data, systematic scientific studies, and models are used to charac-

terize where, when, and why the Nation's water quality is degraded—and what can be done to improve and protect the water for human and ecosystem needs. This information is critical to our future because the Nation faces an increasingly complex and growing need for clean water to support people, economic growth, and healthy ecosystems.

Overview of Major Findings and Implications

There are millions of possible chemical mixtures in drinking-water sources, and their interactions are not well understood.

This report contains the major findings of national and regional assessments of the quality of groundwater in the Principal Aquifers of the United States. The Principal Aquifers, more than 60 in number, are regionally extensive aquifers that supply most of the groundwater pumped across the Nation for drinking water, irrigation, and other uses.

About 130 million people in the United States rely on groundwater for drinking water, and the need for high-quality drinking-water supplies becomes more urgent as our population grows. Although groundwater is a safe, reliable source of drinking water for millions of

people nationwide, high concentrations of some chemical constituents can pose potential human-health concerns. Some of these contaminants come from the rocks and sediments of the aquifers themselves, and others are chemicals that we use in agriculture, industry, and day-to-day life. When groundwater supplies are contaminated, millions of dollars can be required for treatment so that the supplies can be usable. Contaminants in groundwater can also affect the health of our streams and valuable coastal waters. By knowing where contaminants occur in groundwater, what factors control contaminant concentrations, and what kinds of changes in groundwater quality might be expected in the future, we can ensure the availability and quality of this vital natural resource in the future.

Contaminants from geologic or man-made sources were a potential human-health concern in one of every five wells sampled in the parts of aquifers used for drinking water

Groundwater from 22% of sampled wells—more than one in five—contained at least one chemical constituent at a concentration greater than a U.S. Environmental Protection Agency Maximum Contaminant Level (MCL) or other human-health benchmark for concentrations in drinking water. Most of these contaminants were from geologic sources—for example, arsenic, manganese, radon, and uranium. Nitrate was the only constituent from manmade sources that exceeded its human-health benchmark in more than 1% of wells.

This article is adapted from a 2015 report by the U.S. Geological Survey, Circular 1360, Water Quality in Principal Aquifers of the United States, 1991-2010. The complete report is available at <http://pubs.usgs.gov/circ/1360/>.

Differences in geology, hydrology, geochemistry, and chemical use explain how and why aquifer vulnerability and concentrations of contaminants vary across the Nation

The geologic and manmade sources of contaminants that are present, how groundwater moves through an aquifer, and geochemical conditions within aquifers all affect concentrations of contaminants in groundwater. Because these factors differ among Principal Aquifers, different contaminants occur more—or less—frequently in some aquifers than in others. An understanding of how geology, hydrology, geochemistry, and chemical use affect the concentrations of individual contaminants is essential to explaining how and why groundwater quality varies across the Nation. In-depth regional assessments, based on comprehensive sampling of 6,600 wells and ancillary data, provided this understanding for the major contaminants in each Principal Aquifer, and, in some cases, have allowed us to predict concentrations across wide areas. This information also can be used to assess aquifer vulnerability and design efficient and effective

programs for monitoring the Nation's groundwater resources.

Changes to groundwater flow have also altered groundwater quality

People's use of water, through irrigation, pumping, artificial recharge, and drainage, has drastically changed how

The restoration of groundwater supplies that have become contaminated is difficult, is costly, and can take decades

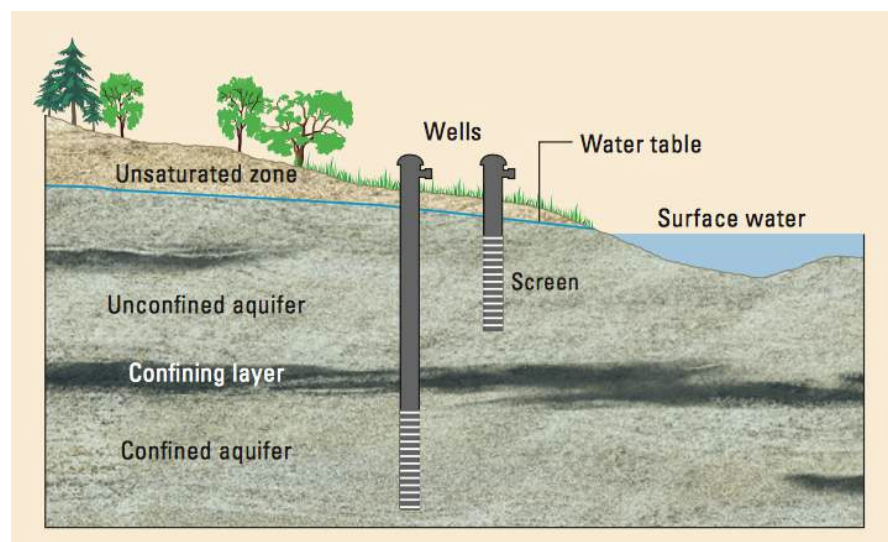
water moves through some aquifers. In some parts of the western United States, the amount of water that flows through aquifers has doubled, tripled, or increased by even more. Such large changes have affected contaminants from both manmade and geologic sources. Irrigation and pumping have

made the deep parts of some aquifers, which are used for drinking water, more vulnerable to contamination by nitrate, pesticides, and other manmade chemicals. Irrigation and other sources of artificial recharge have increased concentrations of dissolved solids in some shallow aquifers in dry climates. Irrigation, pumping, and artificial recharge, by mixing waters of different chemistry, have sometimes had the unexpected consequence of releasing contaminants, such as uranium, selenium, or radium, from aquifer rocks and sediment into the groundwater.

Our actions today are determining groundwater quality for decades to come

Groundwater quality changes slowly. However, indicators of human influence on groundwater quality are increasing across the Nation, even over the relatively short time periods of single decades. Concentrations of dissolved solids, chloride, and/or nitrate in groundwater increased in two-thirds of groundwater well networks that were sampled at 10-year intervals between the early 1990s and 2010. People's influence on groundwater quality also is apparent in the concentrations of nitrate, pesticides, and other manmade chemicals found in shallow groundwater beneath agricultural and urban land. Concentrations of these chemicals exceeded human-health benchmarks two to four times more frequently in shallow groundwater beneath agricultural and urban land than in groundwater from the deeper parts of aquifers currently used for drinking water. Over time, the changes that we see in shallow groundwater are likely to appear in the deeper parts of aquifers, as the shallow groundwater moves downward. This change in quality of deeper aquifers is a concern for the future because the restoration of groundwater supplies that have become contaminated is difficult, is costly, and

Anatomy of an Aquifer



can take decades. In parts of many aquifers, we are still seeing the effects of contaminant inputs from more than 30 years ago; similarly, our actions today are determining groundwater quality for decades to come.

Principal Aquifers and NAWQA Approach to Assessing Groundwater Quality

Water Use

Each day, about 80 billion gallons of water is pumped from the Nation's aquifers. This water is used for drinking water, to irrigate crops and lawns, in industry, for aquaculture and livestock, in mining, to cool power plants, and for many other purposes. Groundwater provides one-third of the water that is pumped by public-supply systems to provide the water used in homes, schools, and businesses in cities and towns. Use of groundwater for public supply has quadrupled during the past 60 years, as the population has steadily increased and cities and suburbs have

expanded. Groundwater also is used for drinking water by rural homeowners with privately-owned household (domestic) wells. Overall, about 130 million people currently get their drinking water from groundwater sources in the United States.

The Principal Aquifers assessed in this circular provide about 90% of the groundwater pumped for public supply, irrigation, and other uses nationally. The largest withdrawals are from the unconsolidated sand and gravel aquifers, and most of this water is used for irrigation. Public supply is the largest use of water pumped from the glacial aquifers and from most carbonate-rock, sandstone, and semiconsolidated sand aquifers. Water withdrawals for domestic supply are small compared with other withdrawals for public supply and irrigation in nearly all aquifers. However, about 43 million people, or 15% of the total population of the United States, rely on private wells for their drinking water. Many of these people live in rural areas where there is no other source of drinking water available. Groundwater

quality is of particular concern for domestic well users because there are no regulations that require routine testing or treatment for contaminants in domestic wells in most States.

In parts of the Nation where the population is growing, the demand for water is increasing. Groundwater will become an increasingly important water source, especially in areas where supplies of water withdrawals from lakes, rivers, and reservoirs are limited. For example, new communities in the Denver Basin area that are without available surface water rely on groundwater sources, and withdrawals from the deep sandstone aquifers have tracked population growth. In the upper Midwest, new water withdrawals from the Great Lakes, which supply water to large population centers, are limited to communities within the watershed; suburban communities outside the watershed rely on groundwater supplies to support their growing water demand. Groundwater sources of sufficient quality to meet these existing and future water needs are critical for economic development and human health.

What is a contaminant?

Contaminants have a wide range of sources, both manmade and geologic. Most organic chemicals in groundwater that are of concern for human health are manmade. In contrast, most inorganic constituents in groundwater have geologic or other natural sources, although their concentrations in groundwater may be altered by human activities, such as irrigation and groundwater pumping. Some contaminants have both manmade and natural sources. For example, nitrate in groundwater has many natural sources, but nitrate concentrations in groundwater underlying agricultural and urban areas commonly are higher than in other areas because of contributions from sources associated with human activities.

In this article, a contaminant is defined as any physical, chemical, biological, or radiological substance or matter in groundwater that is manmade or that impairs the use of water for its intended purpose. Impairment is determined by comparing a measured concentration to benchmarks or guidelines. By this definition, all manmade compounds, such as pesticides and volatile organic compounds, are contaminants because they do not occur naturally in groundwater. If a constituent with a geologic source, such as arsenic, occurs in drinking water at a concentration above its human-health benchmark, it also is considered a contaminant.

Land Use

The Principal Aquifers lie underneath diverse types of land use. These land uses can affect the quality of water that infiltrates from the land surface and recharges groundwater. To study the effects of human activities on groundwater, NAWQA studies of shallow groundwater were located in areas of agricultural and urban land uses; these types of land use can result in large alterations of the land surface. Nationally, agricultural land use is most common in the central United States, and urban land use is most common in the East. However, parts of all aquifers across the Nation are overlain by some agricultural and urban land use.

Land use changes with time and these changes can affect water quality. Na-

Renewable Natural Resources Foundation

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tionally, the amount of developed land in the United States increased by nearly 43 million acres, or 60%, between 1982 and 2010, mostly from conversion of forest and agricultural land; this increase is an area roughly the size of Oklahoma. Chemical use, waste disposal, and irrigation that accompany the new development in urban and suburban areas are sources of contaminants to the underlying aquifer. When suburbs and cities expand into cropland, fertilizers and pesticides used in agriculture can be replaced with chemicals associated with residential activities, such as

volatile organic compounds (VOCs) or deicing chemicals, as potential contaminants to underlying groundwater.

The Quality of Groundwater Resources for Drinking and Other Uses

Is this water suitable for human consumption? This important and frequently asked question can be addressed by comparing the chemical constituents of the water to human-health benchmarks—guidelines and standards for concentrations in drinking water that are con-

sidered protective of human health. Nationally, nearly 80% of the 3,700 wells sampled in drinking-water aquifers had concentrations of measured chemical constituents less than human-health benchmarks. About 20% of wells, however, had at least one contaminant present at a concentration greater than the human-health benchmark for that contaminant. Contaminants from geologic sources were responsible for 78% of the concentrations that exceeded a human-health benchmark.

Sixteen contaminants—11 from geologic sources and 5 from human sources—accounted for nearly all (98%) of the instances in which concentrations were greater than human-health benchmarks in wells sampled in drinking-water aquifers. Another 16 constituents exceeded their benchmarks in samples from only 1 or 2 wells. Some of the potential health effects associated with elevated concentrations of these contaminants in drinking water include an increased risk of cancer; various neurological, developmental, and reproductive effects; liver problems; and blue-baby syndrome. Concentrations that are greater than human-health benchmarks are of particular concern in drinking water supplied by domestic wells because routine inspection or testing of these wells is not required.

Because of differences in geology, hydrology, geochemistry and biogeochemistry, and overlying chemical use among aquifers, contaminants can exceed human-health benchmarks much more—or less—frequently in individual aquifers than the national statistics indicate.

Microbiological Contaminants

In addition to chemical constituents, groundwater can contain microbiological contaminants that can be of concern for human health. Microbiological contaminants were assessed by measuring *Escherichia coli* (E. coli) and other indi-

cator organisms in a subset (about 1,400) of the wells sampled in NAWQA Principal Aquifer studies. *E. coli* is a type of bacteria that can signal the presence of fecal contamination and can be associated with pathogenic microorganisms. *E. coli* was detected in 8% of the wells, indicating the potential importance of microbiological contaminants in untreated groundwater. *E. coli* and other indicator organisms were detected more frequently in carbonate-rock and crystalline-rock aquifers than in aquifers of other rock types.

Shallow Groundwater Beneath Agricultural and Urban Land—A Concern for the Future?

Nitrate or manmade organic chemicals (pesticides or VOCs) exceeded a human-health benchmark in 24% of the shallow wells beneath agricultural areas—four times more frequently than in wells in the deeper parts of aquifers used for drinking water, underlying mixed land uses. Eleven percent of shallow wells beneath urban areas had a concentration of nitrate or a manmade organic chemical greater than a human-health benchmark. Elevated concentrations of contaminants from human activities are more common in shallow groundwater in agricultural and urban areas because shallow groundwater is both younger and more heavily influenced by chemical use at the land surface than is deeper groundwater. Eventually, the shallow groundwater is likely to move downward into the aquifer, where it may threaten the quality of future water supplies. Whether the contaminants in shallow groundwater reach the parts of an aquifer used for drinking-water supply depends on the physical and chemical processes that affect the movement of the chemicals through an aquifer. Movement of contaminants into deeper aquifers also depends on whether there are alterations to the groundwater flow system, such as groundwater with-

drawals for water supply, that accelerate the downward movement of shallow groundwater.

Other Water Quality Concerns

Nuisance Contaminants in Drinking Water

Health concerns are not the only criteria by which we judge the quality of our drinking water. In fact, often the most noticeable qualities that determine whether water is acceptable to consumers result from constituents that

About 20% of wells...had at least one contaminant present at a concentration greater than the human-health benchmark for that contaminant.

cause problems such as unpleasant taste or odor, staining, poor reaction with soap, or mineral buildup in pipes and plumbing. Iron, manganese, hardness, pH, total dissolved solids, and several major ions factor into these unwanted effects, which are a common reason why household water-treatment systems are used. The USEPA recommends limits, called Secondary Maximum Contaminant Levels (SMCLs), for these constituents in public water supplies. Overall, 55% of the wells sampled in the parts of aquifers used for drinking water had levels of one or more unwanted constituents or properties outside of USEPA recommended values for drinking water.

Quality of Water for Irrigation

More groundwater is pumped from the Nation's Principal Aquifers for irrigation than for any other use. Quality requirements for irrigation water generally are less stringent than those for drinking water. However, elevated concentrations of dissolved solids—a measure of the salinity of the water—and several other constituents can reduce the yield of agricultural crops and damage soils. Concentrations of dissolved solids between 450 and 2,000 milligrams per liter (mg/L) in water can lead to slight to moderate restrictions on its use on crops, and concentrations greater than 2,000 mg/L can severely limit use. Elevated concentrations of boron, sodium, and chloride also can lead to restrictions on the use of water for irrigation. Nationally, 21% of wells from drinking-water aquifers had concentrations of dissolved solids greater than 450 mg/L, and 1.7% had concentrations greater than 2,000 mg/L. In shallow groundwater beneath agricultural areas, 32% of wells had concentrations of dissolved solids greater than 450 mg/L, and 2.2% had concentrations greater than 2,000 mg/L. Most of the wells with concentrations greater than 2,000 mg/L, which would severely restrict the use of the water for irrigation, were from unconsolidated or sandstone aquifers in the western United States or from deep, confined aquifers.

Quality of Groundwater Flowing to Streams and Coastal Waters

Groundwater in many aquifers ultimately flows into streams, lakes, or coastal waters. Consequently, groundwater quality can affect aquatic life or the beneficial uses—such as fisheries and recreation—that we derive from these waters. Nitrogen (primarily nitrate in groundwater) and phosphorus are of particular concern because they can cause excessive plant growth, noxious

algal blooms, and depleted dissolved oxygen, which are among the top impairments that degrade our streams, lakes, and estuaries. Groundwater contributions to streams, lakes, and estuaries are not obvious and are hard to measure. Studies have shown, however, that groundwater discharge can provide as much as 50% of the flow and nitrogen load delivered to streams that drain to sensitive coastal waters, such as the Chesapeake Bay. Under such conditions, groundwater quality is essential to consider when developing programs to reduce contaminant loads, such as Total Maximum Daily Loads (TMDLs), to coastal waters.

Understanding Where and Why Constituents from Geologic Sources Occur

As groundwater flows, it reacts with the diverse minerals, rocks, and sediments that make up the aquifer and soil. Chemical constituents are released into the groundwater from these geologic sources. Some of these constituents can be a concern for human health, when present in drinking water, or may make the water less desirable for other uses. Differences in geology, recharge rates, groundwater residence times, and geochemical conditions contribute to differences in chemical concentrations among and within Principal Aquifers. Despite these complexities, regional patterns in the distribution of constituents from geologic sources can be recognized and, in many cases, understood.

Arsenic

Arsenic occurs naturally as a trace component in many rocks and sediments. Whether the arsenic is released from these geologic sources into groundwater depends on the chemical form of the arsenic, the geochemical conditions in the aquifer, and the bio-

geochemical processes that occur. Arsenic also can be released into groundwater as a result of human activities, such as mining, and from its various uses in industry, in animal feed, as a wood preservative, and as a pesticide. In drinking-water supplies, arsenic poses a problem because it is toxic at low levels and is a known carcinogen. In 2001, the USEPA lowered the MCL for arsenic in public-water supplies to 10 micrograms per liter ($\mu\text{g/L}$) from 50 $\mu\text{g/L}$.

Arsenic was detected in nearly half of the wells sampled in parts of aquifers used for drinking water (41% of wells,

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concentrations greater than 1 $\mu\text{g/L}$). Detections were more common and concentrations generally were higher in the western United States, especially in several unconsolidated sand and gravel aquifers and in a carbonate-rock aquifer, than in the East. Concentrations were greater than the MCL in 6.7% of all wells sampled in the parts of aquifers used for drinking water. In about half of the aquifers included in these assessments, at least one well sampled contained arsenic at a concentration that exceeded the MCL. Processes that cause arsenic to accumulate in groundwater are complex and differ among aquifers.

Radionuclides

Many people might be surprised to learn that drinking-water sources can contain radioactive elements (radionuclides). Radionuclides in groundwater are primarily from geologic sources and include isotopes of uranium, radon, radium, polonium, and lead. Rock type, groundwater geochemistry, and, in some cases, human modifications to flow systems influence the distribution of radionuclides in groundwater. The radioactive decay process itself adds complexity because radionuclides transform into different elements. Radionuclides in drinking-water sources can be a concern for human health because several are toxic or carcinogenic.

Uranium

Uranium is a common trace element in many rock types, but it is particularly enriched in crystalline rocks, such as granites, and in sediments derived from crystalline rocks. Although weakly carcinogenic, uranium is chemically toxic, and is a concern for human health because it causes kidney damage at elevated concentrations when consumed in drinking water. Uranium was detected (concentrations greater than 1 $\mu\text{g/L}$) in 35% of wells sampled in the parts of aquifers used for drinking water but exceeded the USEPA MCL of 30 $\mu\text{g/L}$ in only 1.6% of samples nationally. Concentrations in groundwater were higher in the western United States than in the East.

Radon

Radon (radon-222) is present in most groundwater in the United States and was detected in 94% of wells sampled in the parts of aquifers used for drinking water. Radon in water is a dissolved gas that does not react with other chemicals. When water that contains radon is used in a home, most of the radon is released

from the water into the air and can be inhaled. Inhalation of radon poses a risk of lung cancer. The USEPA has proposed an MCL of 300 pCi/L and an Alternative MCL (AMCL) of 4,000 pCi/L for radon in public water systems. The lower proposed MCL for radon would apply to States and public water systems that do not develop programs to address health risks from radon in indoor air; the higher proposed AMCL would apply to States and public water systems that have established such programs. Concentrations exceeded the lower proposed MCL in 64% of wells, including at least one well from every Principal Aquifer in this study. The proposed AMCL was exceeded in only 3.6% of wells. Most of the concentrations greater than 4,000 pCi/L were measured in crystalline-rock aquifers in the Northeast, the mid-Atlantic region, and Colorado.

Manganese

Manganese is a nuisance in water supplies because it stains plumbing and laundry, but it can be a health concern as well because it can cause neurological effects at elevated concentrations. Manganese is a metallic element that is present in igneous, metamorphic, and sedimentary rocks. Though common in aquifer rocks and sediments, manganese occurs in groundwater only when concentrations of dissolved oxygen are low. Nationwide, concentrations of manganese were greater than the human-health benchmark of 300 µg/L in about 7% of the wells sampled in the parts of aquifers used for drinking water. Concentrations generally were higher in the eastern United States than in the West. However, redox conditions can be quite variable within most aquifers, and manganese concentrations greater than the human-health benchmark were measured across the Nation and in at least one well in more than half the aquifers included in this study.

Dissolved Solids

Is the water freshwater or salt water? This question is answered by the water's concentration of dissolved solids, which is a basic characteristic of all natural waters. Freshwater generally has dissolved solids concentrations less than 1,000 mg/L. Even in freshwater, however, dissolved solids in water can cause problems that impair water use. These include unpleasant taste, higher water-treatment costs, accumulation of minerals in plumbing, staining, corrosion, reduced equipment lifespan, and restricted use for irrigation. Concentrations less than 500 mg/L are recommended by the USEPA for public water supplies to

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avoid these problems in drinking water. When used for irrigation, water with high dissolved solids can reduce crop yield because the dissolved salts make it more difficult for plants to extract water from the soil. Dissolved solids in irrigation water can cause salts to build up in soils and aquifers (salinization) and can eventually make the land unsuitable for agriculture.

Climate, geology, and groundwater age influence concentrations of dissolved solids in groundwater. Human activities can also influence concentrations of dissolved solids at a variety of scales, across large irrigated areas or at the sites of individual septic systems or pumping wells.

Human activities can add dissolved solids to recharging groundwater. Detergents, water softeners, fertilizers, road salt, urban runoff, and animal and human waste are some of the human sources that are delivered to groundwater by wastewater disposal, septic systems, or direct application to land surface. Irrigation can cause dissolved solids in groundwater to increase in arid and semiarid regions. As a result, dissolved solids concentrations may be higher in shallow, recently recharged groundwater near the water table beneath urban, suburban, or agricultural areas than in shallow groundwater beneath undeveloped areas or in deeper groundwater.

Understanding Where and Why Contaminants from Human Activities Occur

Activities associated with agriculture, industry, and urbanization all can contribute contaminants to groundwater. Many of these contaminants, such as industrial solvents and pesticides, are manmade chemicals that have no natural sources. Others, such as nitrate and chloride, have geologic sources, but human activities greatly increase their concentrations in groundwater relative to natural levels. Where, when, and how chemicals are used influence the occurrence of these contaminants in groundwater. Chemical characteristics influence how contaminants are transported through soils and in groundwater; geochemical processes and biodegradation can alter contaminant concentrations as they move along flow paths.

Nitrate

Synthetic fertilizer use, waste disposal, and fossil-fuel combustion have greatly increased the amount of biologically available nitrogen in the environment. As a result, concentrations of nitrate, the primary form of nitrogen in

groundwater, have increased. Nitrate in groundwater used for drinking water is a health concern, and the USEPA has set an MCL for nitrate of 10 mg/L as nitrogen (N) to protect against methemoglobinemia, or blue baby syndrome. Nitrate-rich groundwater can also cause problems when it is discharged into lakes, rivers, or the ocean because nitrogen stimulates algal and plant growth and can lead to anoxia and eutrophication. In most instances, concentrations of nitrate in groundwater that are high enough to pose human-health or ecological risks result from human activities.

Nitrate concentrations were greater than the MCL of 10 mg/L as N in about 4% of wells sampled in drinking-water aquifers, placing nitrate among the top four contaminants in terms of how frequently concentrations exceeded human-health benchmarks. More than one-third of wells sampled in the parts of aquifers used for drinking water had nitrate concentrations greater than 1 mg/L as N, a level that indicates the likely influence of human activities in most parts of the Nation. Concentrations were considerably higher in shallow groundwater beneath agricultural land than in shallow groundwater beneath urban areas or in deeper groundwater used for drinking-water supplies: 22% of wells in agricultural settings had concentrations greater than the MCL, and nearly two-thirds had concentrations greater than 1 mg/L as N. Elevated concentrations of nitrate in shallow groundwater are a concern because shallow groundwater in some agricultural areas is used for domestic water supply. Further, shallow groundwater beneath agricultural or urban land can move downward into deeper parts of the aquifer that are used for drinking water or may contribute to excess nitrogen in streams and coastal waters.

Where and Why are Nitrate Concentrations High?

Nitrogen use and release (nitrogen inputs) across the landscape, physical features that control how fast water flows through soils and aquifers, and redox conditions are the three main factors that influence nitrate concentrations in groundwater. Nitrogen inputs are widespread and include fertilizers applied to crops, lawns, and turf; septic systems; and precipitation and dry deposition. As a result, high concentrations of nitrate were distributed broadly across the Nation, especially in shallow groundwater beneath agricultural land. Nitrogen inputs from farm fertilizer are the largest source of nitrogen nationally.

High concentrations of some chemical constituents [in groundwater] can pose human-health concerns.

Measured nitrate concentrations, nitrogen sources, and factors associated with water transport and denitrification potential can be used to predict nitrate concentrations in groundwater across the United States. These results can be used to identify areas that might warrant additional monitoring or are especially vulnerable to nitrate contamination.

Pesticides and Volatile Organic Compounds

Pesticides and volatile organic compounds (VOCs) are pervasive in modern life. They are used in agriculture, industry, transportation, and many day-to-day activities around the home. Thousands of different chemicals have been

manufactured for use in the United States. Many of these chemicals are toxic and can pose human-health or ecological concerns in drinking water or in the environment. Groundwater samples from the Principal Aquifers were analyzed for about 240 pesticides and VOCs, with a focus on those that are most heavily used.

Pesticides and VOCs can reach groundwater through infiltration in recharge from the land areas where they are applied, through accidental spills or leaks, or through waste disposal. Which chemicals reach groundwater depends to a large extent on their use, but it also depends on the properties of the chemicals. Chemical characteristics—such as water solubility, volatility, density, and sorption properties—determine the mobility of a chemical through soils and aquifers. Many pesticides and VOCs degrade in soils and groundwater into other chemicals; a chemical's resistance to degradation (persistence) also will determine if it is detected in groundwater. Mobility and persistence, in turn, are affected by geochemical conditions in the aquifer.

How Often Were Pesticides and VOCs Detected and Are They Health Concerns?

Pesticides and VOCs were frequently detected in groundwater, and all Principal Aquifers are vulnerable to contamination by these chemicals. Pesticides were detected in 32% and VOCs were detected in 40% of wells sampled in the parts of aquifers used for drinking water. Concentrations of individual pesticides and VOCs were mostly low (less than 0.2 µg/L), however, and human-health benchmarks were rarely exceeded. Detections and benchmark exceedances were more frequent in shallow groundwater beneath agricultural and/or urban land than in deeper groundwater used for drinking water. The shallow groundwater that was sam-

pled represents recently recharged groundwater present in a large part of the United States that will move deeper into aquifers, potentially affecting future drinking-water supplies.

Although they rarely exceeded existing human-health benchmarks as individual chemicals, pesticides and VOCs often occurred in groundwater as mixtures. Mixtures of pesticides or VOCs were present in about 40% of groundwater samples from parts of aquifers used for drinking water, in 68% of samples of shallow groundwater beneath agricultural land, and in 82% of samples of shallow groundwater beneath urban land. Mixtures are a potential concern because the human-health effects of some chemicals may be additive. There are millions of possible chemical mixtures in drinking-water sources, and their interactions are not well understood.

Which Pesticides and VOCs Were Detected and Why?

Herbicides used in agriculture were the most frequently detected type of pesticide. Atrazine (and its degradates), simazine, prometon, and metolachlor were the herbicides most frequently detected. These findings generally reflect patterns of chemical use. Agricultural herbicides account for about 80% of the total amount of conventional pesticides used in the United States, and atrazine and metolachlor have been among the most heavily used agricultural herbicides for the past several decades. Atrazine, simazine, and metolachlor were detected more frequently in shallow groundwater beneath agricultural land than in other settings, whereas prometon, an herbicide used along roads and rights-of-way, was detected more frequently in shallow groundwater beneath urban land.

Trihalomethanes, a group of chemicals that includes byproducts of water chlorination, and solvents were the most

frequently detected types of VOCs. Trihalomethanes and solvents, along with gasoline hydrocarbons, were detected in some wells in nearly every aquifer. Chemicals used in organic synthesis, gasoline oxygenates, fumigants, and refrigerants were detected less frequently overall and in fewer aquifers. As with pesticides, patterns of chemical use help explain some of the differences in distributions of chemical groups in groundwater. Solvents, trihalomethanes, and gasoline hydrocarbons have been used for many decades throughout the United

Pesticides and volatile organic compounds were frequently detected in groundwater, and all Principal Aquifers are vulnerable to contamination by these chemicals.

States. In contrast, use of fumigants and gasoline oxygenates (additives to enhance fuel octane) has been limited to small areas of the country. Gasoline hydrocarbons are used in larger amounts than any other kind of VOC but were less frequently detected than trihalomethanes and solvents. The lower frequency of detections, despite higher use, is because gasoline hydrocarbons also are among the least soluble of the VOCs, tend to sorb to soil and aquifer solids, and biodegrade under oxic conditions, illustrating the importance of chemical characteristics as well as use patterns in the distribution of chemicals in groundwater.

Chloroform, Perchloroethene, and Trichloroethane

Why were chloroform, perchloroethene (PCE), trichloroethene (TCE), and 1,1,1-trichloroethane (TCA) among the most frequently detected VOCs? These chemicals have numerous, widespread sources and a long history of use in the United States.

Chloroform is used in industry but also formed when water is treated with chlorine—when drinking water, wastewater, or pool water is disinfected, for example. Thus, leaky sewers, wastewater discharge, and landscape watering with chlorinated water are potential sources of chloroform to groundwater; these sources that are ubiquitous in residential and urban areas across the Nation. PCE, TCE, and TCA are chlorinated solvents with many commercial and industrial uses, including degreasing and dry cleaning. These VOCs enter groundwater through waste disposal, spills, and leaks. Chloroform, PCE, TCE, and TCA all were detected more frequently in shallow groundwater beneath urban land than in deeper groundwater used for drinking water or in shallow groundwater beneath agricultural land because sources of these VOCs are more common in urban areas than in other areas.

PCE and TCE were among the few pesticides or VOCs that were measured at concentrations greater than human-health benchmarks in groundwater samples. In fact, PCE and TCE accounted for nearly 20% of all instances in which a pesticide or VOC exceeded its human-health benchmark. In contrast, chloroform was rarely present at concentrations of potential human-health concern; samples from only two wells had chloroform concentrations greater than the USEPA MCL (a combined MCL for chloroform and three other trihalomethanes).

Methyl *Tert*-Butyl Ether

Methyl *tert*-butyl ether (MTBE) is an oxygenate that was added to reformulated gasoline during the 1980s and 1990s to reduce air pollution. MTBE in water supplies quickly became a concern when it was detected in public wells in California and other States in the 1990s. Compared with other components of gasoline, MTBE is much more soluble, less likely to sorb to soils or aquifer materials, and more resistant to biodegradation. MTBE enters groundwater from leaking underground storage tanks and other releases of gasoline to the environment. There is no MCL or HBSL for MTBE, but the USEPA recommends concentrations in drinking water less than 20 to 40 µg/L to avoid unpleasant taste and odor. A number of States have adopted MCLs for MTBE in drinking water that range from 10 to 70 µg/L.

The widespread occurrence of MTBE in groundwater, despite its relatively short history of intense use, illustrates how vulnerable shallow groundwater is to contamination by newly introduced chemicals with physical and chemical properties that make them mobile and persistent in the subsurface.

Fumigants

From a national perspective, agricultural fumigants are detected infrequently in groundwater. In most Principal Aquifers, they were not detected at all. However, in areas where they were used, fumigants such as dibromochloropropane (DBCP) and ethylene dibromide (EDB) are still detected in groundwater, and at concentrations higher than their human-health benchmarks decades after their use was banned because of health concerns. The fumigants DBCP, EDB, and DCP cause cancer and other health problems.

Fumigants have been applied extensively in several areas of the United States since the 1950s to control soil

pests in agriculture. In those early days of pesticide use, groundwater was not thought to be vulnerable to contamination from chemicals applied at the land surface. This perception changed, however, when DBCP was detected in 1979 in California's Central Valley aquifer system, two years after its use had been banned there because of reported sterility among manufacturing workers.

These agricultural fumigants are persistent in groundwater; samples for the NAWQA studies were collected between 1993 and 2002, about 25 years

*Irrigation and
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groundwater.*

after the use of DBCP, EDB, DCP, and TCP as agricultural fumigants was discontinued. These VOCs remain in groundwater for a long time because they are highly soluble, do not sorb strongly to soils, and degrade very slowly. Forecasting models predict that concentrations of DBCP in Central Valley groundwater could continue to exceed the MCL for 70 years after the DBCP entered the aquifer and that, similarly, DBCP could remain at detectable concentrations in Oahu groundwater for decades. In the Central Valley, DBCP and the other fumigants are likely to move deeper into the aquifer, potentially affecting public-supply wells in addi-

tion to the domestic wells in which they are currently detected.

How Does Our Use of Water Affect Groundwater Quality?

About 80 billion gallons of groundwater is pumped each day from the Nation's aquifers, and 128 billion gallons per day of water is spread across the landscape for irrigation. This movement of water has altered groundwater flow systems—profoundly in some cases, where the flux of water through aquifers has more than doubled relative to natural conditions prior to development. Whenever water is removed or added to an aquifer, groundwater flow directions, flow rates, and often geochemical conditions change. Consequently, when our use of water alters groundwater flow systems, groundwater quality also is affected, sometimes in unexpected ways.

Large-Scale Flow Alterations in the Western Aquifers

The development of water resources for agricultural, urban, and residential uses in the arid and semiarid West has greatly increased both recharge to and discharge from the aquifers in these areas. Modern rates of recharge and discharge are more than twice the natural, predevelopment rates in some aquifers and basins. Infiltration of excess irrigation water and canal leakage are the two major sources of artificial recharge. Other sources of artificial recharge include leakage from water distribution pipes, sewer lines, and storm drains; septic-system effluent; and engineered infiltration of wastewater and stormwater. The increased discharge results primarily from groundwater pumping. Irrigation and pumping can accelerate the downward movement of manmade contaminants and increase concentrations of dissolved solids in groundwater.

Aquifers with Artificial Recharge are More Vulnerable to Contamination from Human Sources

Artificial recharge from irrigation and other sources increases groundwater flow rates and in many cases adds water to an aquifer in places where there was little or no natural recharge prior to development. This new recharge water can make the aquifers more vulnerable to human sources of contamination because the new recharge water brings contaminants down from the land surface into the aquifer.

In the Central Valley, California, recharge has increased more than six-fold and discharge has increased more than sevenfold with water and land development. Before development, groundwater flowed upward in the valley center and discharged in wetlands and streams. Infiltration of excess irrigation water and pumping from the deep aquifer have reversed the direction of flow so that groundwater now flows downward throughout the valley. In some areas, groundwater that previously discharged to the San Joaquin River, in the southern Central Valley, now flows laterally beneath the river toward pumping wells on the western side of the valley. Downward flow through a confining layer is also enabled by wells that are screened in upper and lower aquifer layers. As a result, both shallow and deeper parts of the aquifer in the center of the valley are more vulnerable to contamination by manmade chemicals from the land surface.

Dissolved Solids Increase in Aquifers with Artificial Recharge

Concentrations of dissolved solids are naturally high in groundwater and soil water in the arid and semiarid West. Irrigation and other sources of artificial recharge, however, have increased those concentrations across widespread areas in parts of the Central Valley, Cali-

fornia Coastal Basin, Basin and Range basin-fill, Rio Grande, and High Plains aquifers or aquifer systems. High concentrations of dissolved solids can restrict the use of the groundwater for drinking water or irrigation. In the Santa Ana Basin in California, intensive water management for dissolved solids is needed to maintain drinking-water supplies. High dissolved solids in irrigation water can reduce crop yields and contribute to soil salinization.

Groundwater Mixing and Geochemical Changes – Trace Elements are Mobilized in Various Hydrogeologic Settings

Upward trends in concentrations of dissolved solids, chloride, and nitrate are indications of human influence on groundwater quality.

Pumping, irrigation, and other flow alterations can mix waters from different sources or from different depths within an aquifer. If the compositions of the mixed waters are different, dissolved constituents can react with one another and with aquifer materials to release naturally occurring trace elements into the groundwater, potentially affecting human or ecosystem health.

Groundwater Mixing Across Aquifer Boundaries – Induced Infiltration and Saltwater Intrusion

Streams and the ocean are natural boundaries for groundwater flow systems. When flow systems are altered by

pumping, flow directions can change, allowing groundwater to mix with seawater or river water. Pumping also can draw deep, saline groundwater up into parts of aquifers used for water supply.

Movement of Pesticide Compounds from Rivers to Aquifers in the Glacial Aquifer System

Many public-supply wells in the glacial aquifer system are near rivers. Thick, permeable glacial deposits in river valleys make these locations favorable for groundwater pumping. Pumping can reverse the natural direction of flow toward rivers, causing water to move from the river into the aquifer, a process called induced infiltration. When this process happens, the aquifer becomes vulnerable to contamination from chemicals in the river.

Upward Movement of Saline Water

When hydraulic heads are lowered by pumping in the freshwater aquifer, the saltwater can move upward or inland to parts of the aquifer used for water supply. This process is called saltwater intrusion. In supply wells in southern Arkansas and northern Louisiana, saltwater intrusion has caused chloride levels to more than double during the past 40 years.

How is Groundwater Quality Changing

Concentrations of chemical constituents in natural waters—even in groundwater—can vary because of year-to-year climatic differences and because natural processes are inherently variable. In contrast, consistent change over time in a particular direction is a trend, and trends in contaminant concentrations raise concerns about the sustainability of groundwater use in future decades. Studying trends in groundwater quality at national or even regional

scales is a large undertaking because of the expense of collecting consistent long-term data over large areas and because changes in response to contaminant inputs might not be apparent for many years. Identifying trends in groundwater quality and investigating their causes, however, is essential to helping water managers prepare for the future. Once contaminants in groundwater reach levels that impair its use, it takes a long time for reductions in contaminant inputs to restore the groundwater to its original quality, if such restoration is possible.

Decadal Trends in Groundwater Quality, Early 1990s to 2010

Upward trends in concentrations of dissolved solids, chloride, and nitrate are indications of human influence on groundwater quality. Concentrations of all three of these constituents are increasing in many parts of the United States. Two-thirds of groundwater study areas had upward trends for concentrations of dissolved solids, chloride, and/or nitrate; these trends were based on repeated sampling of the wells in groundwater study areas at 10-year intervals. Most changes in concentration were measured in young groundwater (groundwater that was recharged since the early 1950s) because young, shallow groundwater is more likely to be affected by recent activities at the land surface than is older, deeper groundwater.

The largest changes in concentrations of dissolved solids and chloride occurred in urban areas of the Northeast and upper Midwest and, for dissolved

solids only, in agricultural areas in the Southwest and Florida. Upward trends in dissolved solids are of particular concern in arid areas of the western United States, where water supplies are scarce and dissolved solids concentrations in groundwater are naturally high, because of the potential limitations that high dissolved solids concentration may place on future uses of groundwater. Upward trends in chloride concentration are a concern where groundwater discharges to streams because of the potential effects of high chloride concentrations on aquatic ecosystems.

Looking Forward

Water-quality trends observed since the early 1990s, the distribution of contaminants in shallow and deep groundwater, and groundwater forecasting models suggest that concentrations of contaminants from human sources are likely to increase in many parts of the Nation's Principal Aquifers. Some of these changes will be the result of past actions—contaminant inputs in past years and decades that are not yet reflected in the quality of groundwater pumped from supply wells or discharged to springs, streams, and estuaries. Other changes will result from the management decisions made and actions taken today and in the future. Information on where contaminants occur, what are the sources of contaminants, and how contaminants are transported through groundwater is critical to understanding the limitations that contaminants may place on future water availability.

Endnotes

(for "Editors Note: Understanding Your Drinking Water," pg. 14)

1 Any synthetic or naturally occurring chemical or any microorganism that is not commonly monitored in the environment but has the potential to enter the environment and cause known or suspected adverse ecological and/or human health effects.

2 WSSC. (n.d.). "Emerging Contaminants."

3 Environmental Working Group. (2009). "National Drinking Water Database."

4 Washington Suburban Sanitary Commission (WSSC). (2014). "2014 Water Quality Report."

5 WSSC. (2014). "WSSC Tap Water Analysis – 2014."

Editor's Note: Understanding Your Drinking Water

Drinking water comes from both ground and surface water sources, both of which are subject to various natural and man-made contaminants. The majority of people in the United States who live in urban areas receive their water from a public water supply. Public drinking water suppliers are required by law to conduct regular tests, and their water must meet the Environmental Protection Agency's (EPA) Drinking Water Standards.

Water suppliers purify and treat source water before distributing it to consumers. Below is a summary of the Washington Suburban Sanitary Commission's (WSSC) 2014 water analysis of the Potomac Water Filtration Plant and its tap water to illustrate what contaminants may remain in the water even after treatment. The WSSC provides drinking water to Montgomery County and Prince George County in the Washington, D.C. metropolitan area.

The WSSC Report measures its detected contaminants against Maximum Contaminant Levels (MCL), as well as Maximum Contaminant Level Goals (MCLG). MCL's are the highest level of a contaminant that is allowed in drinking water and are set as close to the MCLGs as feasible using the best available treatment technology. MCLG's are the level of contaminant in drinking water below which there is no known or expected risk to health, allowing for a margin of safety.

In 2014, WSSC did not violate EPA's Drinking Water Standards (MCL levels) for any regulated contaminants. However, based on a yearly average, several regulated contaminants exceeded MCLGs (Table 1), and WSSC detected numerous unregulated contaminants in its water (Table 2). WSSC also tested for "emerging contaminants"¹ in 2008 and detected atrazine (herbicide), carbamazepine (anti-epileptic pharmaceutical), sulfamethoxazole (antibacterial antibiotic), and estrone (natural human hormone).²

Meeting EPA's existing water quality standards does not ensure the safety of drinking water. For example, the unregulated contaminants identified above have unclear human health effects, and little is known about how various chemicals interact with one another to affect human health. Other undetected chemicals with health risks may also be found in drinking water. With ten trillion pounds of chemicals being produced per year in the United States alone and a broken system for regulating these chemicals, we are routinely exposed to hundreds of potentially toxic substances. For safer drinking water, educate yourself on the quality of your water and choose a filter to help remove contaminants. Access detailed information on the water that flows from your tap by locating your water provider. Additionally, the Environmental Working Group³ maintains a National Drinking Water Database that displays test results over several years.

Substance **Exceeds MCLG Levels?** Table 1. Detected Regulated Contaminants (WSSC 2014 Water Quality Report⁴)

Metals	
Barium	no
Total Chromium	no
Selenium	no
Copper	no
Inorganic Contaminants	
Fluoride	no
Nitrate	no
Disinfection Byproduct Precursor	
Total Organic Carbon	n/a
Radioactive Contaminants	
Gross Alpha	yes
Gross Beta	yes
Radium 228	yes
Bacteriological Contaminants	
Total Coliform	yes
Disinfectant and DBPs	
Residual Chlorine	no
Haloacetic Acids (HAA5)	n/a
Total Trihalomethanes (TTHM)	n/a

Table 2. Detected Unregulated Contaminants (WSSC 2014 Water Quality Report, WSSC 2014 Tap Water Analysis⁵)

Substance	Substance
Metals	Inorganic Contaminants
Aluminum	Boron
Calcium	Chlorate
Iron	Chloride
Hexavalent Chromium	Phosphorous
Magnesium	Sodium
Manganese	Sulfate
Nickel	
Potassium	
Silicon	
Sodium	
Strontium	
Vanadium	
Zinc	

Impacts of Ocean Acidification on Marine Biodiversity

Convention on Biological Diversity

Foreword

Marine and coastal biodiversity—ecosystems, species, and genetic material—provide enormous benefits for human well-being. Hundreds of millions of people rely directly on marine biodiversity for their livelihoods. Oceans are critical to many important global geochemical processes, such as climate regulation and carbon cycling. Ocean ecosystems provide critical life supporting services to the global population and underpin global productivity and well-being.

However, the oceans are facing major threats due to rising levels of carbon dioxide in the atmosphere. In addition to driving global climate change, increasing concentrations of carbon dioxide affect ocean chemistry, impacting marine ecosystems and compromising the health of the oceans and their ability to provide important services to the global community. The impacts of ocean acidification are beginning to be felt in some areas, but future projections indicate even more broad-reaching deleterious impacts if action is not taken.

At its ninth meeting, the Conference of the Parties to the Convention on Bio-

logical Diversity (CBD) raised concerns about the potential impacts of ocean acidification on marine and coastal biodiversity and requested the Executive Secretary, in collaboration with Parties, other Governments, and relevant organizations, to compile and synthesize available scientific information on ocean acidification and its im-

Impacts due to ocean acidification are already underway in some areas and...future projected impacts could have drastic irreversible impacts on marine ecosystems.

pacts on marine biodiversity and habitats. This resulted in the production of CBD Technical Series No. 46, “Scientific Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity,” in 2009.

Since then, the amount of research on ocean acidification has grown enormously, as various governments and organizations around the world expanded their research efforts to gain an improved understanding of the ecological and socioeconomic impacts of ocean

acidification and means to address this pressing threat.

In recognition of the need for the most up-to-date information in addressing this issue, the COP, in decision XI/18, requested the Executive Secretary to collaborate with the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization, relevant scientific groups, other relevant organizations, and indigenous and local communities in the preparation of an updated systematic review on the impacts of ocean acidification on biodiversity and ecosystem functions. The updated review builds upon CBD Technical Series No. 46 to provide a targeted synthesis of the biodiversity implications of ocean acidification for marine and coastal systems, including information on the less-reported paleo-oceanographic research.

The report, CBD Technical Series No. 75, “An updated synthesis of the impacts of ocean acidification on marine biodiversity,” represents an enormous scientific effort by researchers and experts from around the world to synthesize the best available and most up-to-date information on the impacts of changing ocean pH on the health of the world’s oceans. Presented here is an adaptation of the complete report.

Among other findings, the report notes that ocean acidification has increased by around 26% since pre-industrial times, and that based on historical evidence, recovery from such changes in ocean pH can take many thousands of years. The report outlines how ocean

This article is adapted from CBD Technical Series No. 75, An Updated Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity. The complete report is available at <https://www.cbd.int/doc/publications/cbd-ts-75-en.pdf>.

acidification impacts the physiology, sensory systems, and behavior of marine organisms and undermines ecosystem health. It also shows that impacts due to ocean acidification are already underway in some areas and that future projected impacts could have drastic irreversible impacts on marine ecosystems. Despite the growing body of information on ocean acidification, the report points out key knowledge gaps, and in light of the many complex interactions related to ocean chemistry, stresses the difficulty of assessing how future changes to ocean pH will affect marine ecosystems, food webs, and the goods and services they provide.

The report presents complex scientific information on ocean acidification in a clear and understandable way and provides an important reference point for scientists, policymakers, and others in understanding how ocean acidification affects our oceans and the vital services they provide. As the need for urgent action to address acidification becomes ever more pressing, collaboration among governments and organizations in enhancing and sharing knowledge will become increasingly important.

What is Ocean Acidification?

Ocean acidification, often referred to as the “other CO₂ problem,” is a direct result of rising atmospheric carbon dioxide (CO₂) concentrations due to the burning of fossil fuels, deforestation, cement production, and other human activities. As atmospheric CO₂ increases, more enters the ocean across the sea surface. This process has significant societal benefits: by absorbing around a quarter of the total human production of CO₂, the ocean has substantively slowed climate change. But it also has less desirable consequences, since the dissolved CO₂ affects seawater chemistry, with a succession of potentially adverse impacts on marine biodiversity, ecosystem services, and human society.

The starting point for such changes is an increase in seawater acidity, resulting from the release of hydrogen ions (H⁺). Acidity is measured on the logarithmic pH scale, with H⁺ concentrations at pH 7.0 being 10 times greater than at pH 8.0. Since pre-industrial times, the mean pH in the surface ocean has dropped by 0.1 units, a linear-scale increase in acidity of ~26%. Unless CO₂ emissions are rapidly curtailed, mean surface pH is projected—with a high degree of certainty—to fall by a further ~0.3 units by 2100, representing an acidity increase of around 170% compared to pre-industrial levels. The actual change will depend on future CO₂ emissions, with both regional and local variations in the oceanic response.

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similar proportion.*

Many scientific studies in the past decade have unequivocally shown that a wide range of marine organisms are sensitive to pH changes of such magnitude, affecting their physiology, fitness, and survival, mostly (but not always) in a negative way. The consequences of ocean acidification for marine food webs, ecosystems, biogeochemistry, and the human use of marine resources are, however, much less certain. In particular, ocean acidification is not the only environmental change that organisms will experience in the future, since it will

occur in combination with other stressors (e.g., increasing temperature and deoxygenation). The biological effects of multiple stressors occurring together cannot be assumed to be additive; instead, due to interactions, their combined impacts may be amplified (through synergism) or diminished (antagonism). Furthermore, there is now evidence that some—but not necessarily all—organisms may show genetically mediated, adaptive responses to ocean acidification.

Marine organisms are currently subject to many other environmental changes in addition to ocean acidification, with the potential to degrade or disrupt ecosystems. Most of these drivers are directly or indirectly due to human activities. They can be broadly grouped into local/regional stressors, for example, due to over-fishing, habitat loss/destruction, pollution, and enhanced nutrient loading (with associated eutrophication and low oxygen), and global-scale, climate-related impacts that are mostly temperature-driven, such as changes in stratification, mixing, and other circulation changes, reduced high latitude surface salinity (due to ice melt and river run-off), de-oxygenation, and increased ultra-violet (UV) radiation. Key issues relating to the three main global-scale stressors—acidification, warming, and de-oxygenation—are summarized in Table 1.

This review provides an updated synthesis of the impacts of ocean acidification on marine biodiversity based upon current literature, including emerging research on the geological history of natural ocean acidification events and the projected societal costs of future acidification.

Table 1. Summary of the causes and impacts of the three main global-scale stressors that will increasingly affect marine biodiversity, with severity of impacts depending on future emissions of greenhouse gases. Note that there may be reinforcing or ameliorating interactions for biological responses to these stressors, and that there are likely to be additional interactions with a wide variety of other environmental parameters, at both global and local scales.

Stressor	Causes	Results	Direct effects	Impacts, including climatic feedback
Acidification	- Increasing CO₂ in atmosphere - Some local contributions (eutrophication, industrial emissions)	- Change in ocean pH and carbonate chemistry - Progressive dissolution of calcium carbonate	- Reduced calcification and growth in many species - Reef erosion - Changes in carbon: nitrogen ratio	- Reduced abundance of calcifying species; other food web changes - Effects on aquaculture and human food supply - Risk of coral extinctions, with habitat loss and increased coastal erosion - Reduced ocean uptake of CO₂ - Potential warming feedback via DMS and cloud formation
Warming	Increasing greenhouse gases in atmosphere	- Temperature increase - Less ocean mixing due to increased stratification - Loss of polar sea ice - More freshwater run-off in polar regions (reducing salinity) - Sea-level rise	- Reduced solubility of CO₂, O₂ and calcium carbonate - Reduced productivity where more stratified; increased productivity in Arctic - Physiological effects on organisms (metabolism, growth and survival)	- Poleward shift of (mobile) species' ranges - Coral bleaching - Changes in community composition and food webs - Global reduction in marine productivity - Reduced ocean uptake of CO₂ - Reduced carbon export to ocean interior
De-oxygenation	- Warming reduces O₂ solubility - Stratification reduces O₂ supply to ocean interior - Local causes: eutrophication	Reduced O₂ availability for respiration, especially in productive regions and mid/deep water	Slower metabolism and growth of zooplankton and fish	- Effects on abundances and distributions - Shift to organisms tolerant to low O₂ (mostly microbial) - Reduced fishery yield - Increased marine production of methane and nitrous oxide (greenhouse gases)
All three together	Increasing CO₂ and other greenhouse gases	Combined stress of reduced pH, warming and low dissolved O₂	- Damage to organism physiology and energy balance - Disrupted food webs	- Major changes to ocean physics, chemistry and biology - Biodiversity loss, with impacts on ecosystem services - Risk of multiple positive feedbacks, increasing rate of future climate change

Consequences of Ocean Acidification

Ocean acidification has increased by around 26% since pre-industrial times

In the past 200 years, it is estimated that the ocean has absorbed more than a quarter of the carbon dioxide released by human activity, increasing ocean

acidity by a similar proportion. It is now nearly inevitable that within 50 to 100 years, continued anthropogenic carbon dioxide emissions will further increase ocean acidity to levels that will have widespread and mostly deleterious impacts on marine organisms, ecosystems, and the goods and services they provide. Marine calcifying organisms seem particularly at risk, since additional energy

will be required to form shells and skeletons, and in many ocean areas, unprotected shells and skeletons will dissolve.

International awareness of ocean acidification and its potential consequences is increasing

Many programs and projects are now investigating the impacts of ocean acidi-

fication on marine biodiversity and its wider implications, with strong international linkages. The United Nations General Assembly has urged States to study ocean acidification, minimize its impacts, and tackle its causes. Many United Nations bodies are focusing attention on these issues.

Global status and future trends

Seawater pH shows substantial natural temporal and spatial variability

The acidity of seawater varies naturally on a diurnal and seasonal basis, on a local and regional scale, and as a function of water depth. Coastal ecosystems and habitats experience greater variability than those in the open ocean due to physical, geochemical, and biological processes and terrestrial influences. Recognition of such variability and an understanding of its causes is crucial to the valid interpretation of observation studies and the assessment of anthropogenic ocean acidification trends. Several national and international programs are now working to provide high-quality, standardized observations that will lead to key knowledge of carbon system changes in the marine environment. These observations will improve our understanding of present-day variability and our ability to make reliable projections of future conditions.

Substantial natural biological variability exists in organisms' responses to pH changes

Metadata analyses—combining results from many experimental studies—show that there are different, but consistent, patterns in the response of different taxonomic groups to simulated future ocean acidification. There can also be variability in responses within species depending on interactions with other factors.

Surface waters in polar seas and upwelling regions are increasingly at risk of becoming undersaturated

In waters where pH is already naturally low (in high latitudes, coastal upwelling regions, and on the shelf slope), widespread undersaturation of the most common forms of biologically-formed calcium carbonate—aragonite and calcite—is expected to develop during this century. Benthic and planktonic molluscs are amongst the groups likely to be affected, as well as cold-water corals and the structural integrity of their habitats. Undersaturation dissolves shells and skeletons that are not protected by an organic layer.

Recovery from a major decrease in ocean pH takes many thousands of years.

International collaboration is underway

Collaborative efforts will improve monitoring of ocean acidification, closely linked to other global ocean observing systems. A well-integrated global monitoring network for ocean acidification is crucial to improve understanding of current variability and to develop models that provide projections of future conditions. Emerging technologies and sensor development increase the efficiency of this evolving network.

What the past can tell us: paleo-oceanographic research

During natural ocean acidification events that occurred in the geological past, many marine calcifying organisms became extinct.

High atmospheric carbon dioxide has caused natural ocean acidification in the past, linked to “coral reef crises.” During the Paleo-Eocene Thermal Maximum (PETM, ~56 million years ago), the species extinctions were less severe than earlier events. However, the atmospheric changes that occurred then were much slower than those happening today.

Recovery from a major decrease in ocean pH takes many thousands of years

The paleo-record shows that recovery from ocean acidification can be extremely slow. Following the PETM, for example, recovery took around 100,000 years.

Impacts of ocean acidification on physiological responses

Implications for acid-base regulation and metabolism for many marine organisms

When external hydrogen ion levels substantially increase, extra energy may be required to maintain the internal acid-base balance. This can lead to reduced protein synthesis and reduction in fitness. Such effects are greatest for sedentary animals, but can be mitigated if food supply is abundant. In addition, increasing metabolism may offset detrimental effects in some species. The degree to which different groups of organisms are sensitive to changes in carbonate chemistry has become a major focus of ocean acidification research.

Impacts on invertebrate fertilization success

Impacts on fertilization success are highly variable, indicating the potential for genetic adaptation. Experimental studies on the impact of ocean acidification on fertilization show that some species are highly sensitive, while others are tolerant. This variation reflects the biological reality that some species have relatively greater tolerance. However, the variability almost certainly also results from different experimental approaches. Intra-specific variability indicates the scope for a multi-generational, evolutionary response. There is some hope that adaptation by selection of tolerant genotypes may occur. Understanding the basis of variation in responses to elevated CO₂ among individuals will be key to making predictions about the potential for adaption to rising CO₂ levels.

Ocean acidification is potentially detrimental for calcifying larvae

Larval shells are among the smallest and most fragile shells in the ocean and are potentially extremely vulnerable to decreased mineral saturation caused by ocean acidification. Early life stages of a number of organisms seem to be particularly at risk from ocean acidification, with impacts including decreased larval size, reduced morphological complexity, and decreased calcification. Non-calcifying larvae, including coral and some sea star larvae, are generally more resilient than calcifying larvae to near-future acidification. However, some non-calcifying species still show negative responses to acidification, and long-term experiments show that acidification of the parental environment can lead to impaired larval growth in species that are resilient in shorter-term experiments. Understanding how effects at early life-stages can “carry-over” to influence growth and re-

production of the adult remains a significant challenge and knowledge gap.

Altered sensory systems and behavior in fish and some invertebrates

Reef fish larvae exposed to elevated CO₂ lose their ability to discriminate between ecologically important chemical cues, such as odors from different habitat types, kin and non-kin, the smell of predators, and visual function. Response to auditory cues is altered, be-

Impaired behavior at all life stages occurs as a result of permanent exposure to CO₂ levels that are well within the range that could occur in the ocean this century, with potentially significant effects for functionally and economically important species.

havioral lateralization is lost, and fish are no longer able to learn. Impaired ability to discriminate between olfactory and auditory cues, or attraction to inappropriate cues, could have serious consequences for the ability of larvae to successfully transition from the pelagic to benthic environments. Furthermore, larvae exposed to elevated CO₂ exhibit bolder and riskier behavior once they settle to the reef, potentially leading to higher mortality from predators.

Behavioral effects are not restricted to larvae and juveniles. Recent experiments have shown that adult reef fish

also suffer impaired olfactory ability and altered behavior, with potential effects on predator-prey interactions, habitat selection, and homing to resting sites. A wide range of reef fish species appear to be affected, including important fisheries species such as the coral trout *Plectropomus leopardus*. Impaired behavior at all life stages occurs as a result of permanent exposure to CO₂ levels that are well within the range that could occur in the ocean this century, with potentially significant effects for functionally and economically important species.

Recent work has also considered impacts of ocean acidification on other physiological responses, such as the maintenance of immune function. To date, this work has focused on commercially important species, which are important for the maintenance of global food security. Elevated CO₂ can impact the immune system of marine organisms indirectly, especially if the changes have a negative impact on protein synthesis rates, thus reducing the synthesis of key immune enzymes and peptides. Immune system maintenance has conventionally been regarded as an energetically expensive constraint on an organism's energy budgets, and it has been speculated that even chronic moderate reductions in pH could be significant, especially in resource-limited environments. Additionally, as environmental factors play a significant role in determining the course of infection, climate change has the potential to increase susceptibility to disease.

Impacts on benthic communities

Around half of benthic species have lower rates of growth and survival under projected future acidification

Benthic ecosystems comprise some of the key ocean communities that we rely upon for food and ecosystem services, and they occur throughout the

world's oceans, from the splash zones of all shores to the deepest waters. While none will be able to avoid future acidification, it remains unclear how changes in ocean conditions will affect the composition and function of benthic communities in different environments. For corals, molluscs, and echinoderms, many studies show reduction in growth and survival rates with ocean acidification. However, these responses are variable, and some species can live at low pH conditions. The sensitivity of entire benthic communities to ocean acidification is also expected to be linked to the scale of natural variation in the environment. Populations inhabiting highly variable habitats, such as coastal systems, may possess the phenotypic and genetic diversity to tolerate and perhaps thrive across the range of variation in carbonate parameters.

Many seaweed (macroalgae) and seagrass species can tolerate, or may benefit from, future ocean acidification

Non-calcifying photosynthetic species, which are frequently abundant near natural CO₂ seeps, may benefit from future ocean acidification. Calcifying macroalgae are, however, negatively impacted. High densities of seagrass and fleshy macroalgae can significantly alter the local carbonate chemistry, with potential benefit for neighboring ecosystems.

Impacts on pelagic communities

Many phytoplankton could potentially benefit

Plankton—drifting organisms—are taxonomically diverse, comprising phytoplankton, zooplankton, and heterotrophic bacteria. These plankton, calcifiers and non-calcifiers, form a key component of the marine food chain and also play an important role in biogeo-

chemical cycling. Non-calcifying phytoplankton (e.g., diatoms) can show increased photosynthesis and growth under high CO₂ conditions. The response of calcifying phytoplankton (e.g., coccolithophores) is more variable, both between and within species. Mesocosm experiments—any outdoor experimental system that examines the natural environment under controlled conditions—provide insights into the community shifts that might arise through competitive interactions, as well as the balance between increased photosynthesis and decreased calcification. The response of bacterio-plankton to ocean acidification has not been well studied, but altered decomposition rates would have implications for nutrient cycling.

Planktonic foraminifera and pteropods likely to experience decreased calcification or dissolution

The shells of both of these groups are liable to experience dissolution if calcium carbonate saturation drops below one. Decreases in shell thickness and size of planktonic foraminifera may also decrease the efficiency of future carbon transport between the sea surface and the ocean interior.

Impacts on biogeochemistry

Ocean acidification could alter many other aspects of ocean biogeochemistry, with feedbacks to climatic processes. High CO₂ may alter net primary productivity, trace gas emissions, nitrogen-carbon ratios in food webs and exported particulate matter, and iron bioavailability. The scale and importance of these effects are not yet well understood. The impacts of unmitigated ocean acidification are estimated to represent a loss to the world economy of more than US \$1 trillion annually by 2100.

Impacts on ecosystem services and livelihoods

Impacts on ecosystem services may already be underway

Ecosystem services are the components of nature that help create human well-being and economic wealth. They result from ecological processes, functions, and biodiversity. At a general level, ecosystem services can be categorized into four distinct groups: provisioning services, regulating services, cultural services, and supporting ser-

Box 1. Impact of ocean acidification on oyster hatcheries.

Due to the naturally low and variable pH of upwelled water off the northwest coast of the United States, there is strong evidence that additional acidification due to anthropogenic CO₂ is already having biological impacts in that region—where carbonate saturation values are now at levels projected elsewhere 50-100 years in the future. Established oyster hatcheries in Oregon and Washington have increasingly suffered high larval mortalities (up to 80%) since 2006, threatening the viability of an industry with total economic value of around \$280 million per year. The variable carbonate chemistry and pH of the hatchery water (due to periodic upwelling events) have been shown to be major factors affecting the success of larval production and mid-stage growth cohorts of the Pacific oyster *Crassostrea gigas*. The oyster hatcheries have now adapted their working practices so that they could avoid using very low pH seawater, either by recirculating their seawater or treating their water during upwelling events. With these new practices, the northwest coast oyster hatcheries are producing near to full capacity again.

vices. Ocean acidification is apparently already impacting aquaculture in the northwest United States of America, further decreasing the pH of upwelled water, which has a naturally low saturation state for calcium carbonate.

Supporting services comprise the processes and functions that contribute to all other ecosystem services. For example, many species that are likely to be negatively impacted by pH changes are habitat-forming organisms providing shelter, food, and nursery functions to other marine species, including com-

mercially important fish. They also contribute to coastal protection, leisure, recreation, and other cultural benefits.

Ocean acidification can be expected to affect provisioning services; however, direct evidence is limited. Molluscs and crustaceans harvested for food are likely to be affected as they have calcareous shells and exoskeletons, with sensitivity demonstrated in experimental studies. Field-based evidence of the impact of ocean acidification on molluscs has been reported at sites along the Pacific coast of the United States, where

the failure of oyster reproduction in hatcheries has been attributed to high levels of CO₂ in the water that upwells in that region (Box 1). Impacts such as these may have different implications depending upon their location. For example, small island developing states that are reliant upon shellfish aquaculture for export and protein intake could be particularly vulnerable. Nevertheless, some commercially important species may be able to adapt, or may be naturally resilient. Some other species may be indirectly impacted by ocean

Table 2. Some key research gaps and challenges for future ocean acidification research.

Ocean acidification process	Research question(s)
Biogeochemical	Will future OA provide significant feedback to the global carbon cycle and climate change, through global-scale changes in calcification, ocean productivity, particle sinking in the ocean, and effects on other climatically active gases, e.g., DMS and N ₂ O? Will the ocean become a less important CO ₂ sink in the future, exacerbating atmospheric changes?
Physico-chemical	What is the current variability of ocean carbonate chemistry at ecologically significant temporal and spatial scales, and how will this change under future climate change scenarios, with associated additional changes in temperature, oxygen, stratification, ocean circulation, and river inputs? Which areas of the ocean (e.g., polar regions, upwelling zones, and shelf seas) will experience greatest and most rapid change? Will chemical changes also impact sound transmission in future oceans, with impacts on organism communication?
Physiological and behavioural	What are the unifying mechanisms linking species' molecular, metabolic and behavioural responses to ocean acidification? (e.g., based on energy metabolism and acid-base regulation). Does this explain the high taxonomic variability observed in response to ocean acidification and complex interactions with other stressors (e.g., temperature, low oxygen and food/nutrient availability, ultraviolet radiation)? How would different scenarios of ocean acidification affect the immune system resilience of various species to pathogens?
Genetic	How can information from relatively short-term studies (weeks to months) on individual species be applied to long-term (decadal), multi-generational responses by populations, involving adaptation and evolution? Does genetic variation confer population resilience? How will this impact marine biodiversity?
Ecological	How can experimental studies on ocean acidification impacts be best scaled-up to the ecosystem level where interacting multi-species communities are subject to other environmental changes, i.e., allowing for multi-stressor effects, and recognising that negative (or positive) impacts of ocean acidification on one species may indirectly benefit (or disadvantage) another and thus community composition and biodiversity? How will impacts on one species impact upon others (trophic interactions), and how will this affect food security through the food chain?
Socio-economic	What future socio-economic impacts will arise from ocean acidification? How can we best quantify the risks to non-market ecosystem services (e.g., storm protection provided by tropical coral reefs) as well as to aquaculture and fisheries? Can adaptation strategies be identified for the most vulnerable people and industries? How are various types of communities (from indigenous and local communities to global markets) differentially vulnerable to the impacts of ocean acidification? How can ocean acidification science best contribute to risk management, the sustainable use of natural resources and national/international policy development?

acidification through changes in their food chain and habitat. The economic impacts of ocean acidification on the fisheries industry are relatively understudied. However, models suggest that there may be a substantial reduction in fisheries catch potential under future conditions, affecting the quantity, quality, and predictability of future harvests.

Regulating services include coastal defense and carbon storage. Many marine habitats and ecosystems significantly dissipate the energy in waves reaching the coast, increasing sedimentation rates and decreasing coastal erosion. Changes in these natural communities resulting from ocean acidification would therefore affect their ability to protect the coast. While potential impacts of ocean acidification on corals and bivalves may be negative, this may not be true for seagrasses, which may benefit from higher levels of CO₂ in the water and therefore afford greater protection of the coast.

The impact of ocean acidification on cultural ecosystem services is particularly difficult to assess. While impacts to tourism, leisure, and recreation can be partially quantified, many cultural services are intangible, and the role of biodiversity in these services is unclear. Where marine species and ecosystems are given high inherent worth or are important to indigenous peoples' heritage and identity, their reduction in abundance may result in significant cultural loss.

Resolving uncertainties

Existing variability in organism response

Existing variability in organism response to ocean acidification needs to be investigated further to assess the potential for evolutionary adaptation. Multi-generational studies with calcifying and non-calcifying algal cultures show that adaptation to high CO₂ is possible for

some species. Such studies are more difficult to conduct for long-lived organisms, and variability in adaptive capacity is likely. Even with adaptation, community composition and ecosystem function are still likely to change.

Multiple stressors

Research on ocean acidification increasingly needs to involve other stressors, as will occur under field conditions in the future. Acidification may interact with many other changes in the marine

Models suggest that there may be a substantial reduction in fisheries catch potential under future conditions, affecting the quantity, quality, and predictability of future harvests.

environment, local and global. These "multiple stressors" include temperature, nutrients, and oxygen. *In situ* experiments on whole communities (using natural CO₂ vents or CO₂ enrichment mesocosms) provide a good opportunity to investigate impacts of multiple stressors on communities to increase our understanding of future impacts.

Synthesis

Ocean acidification represents a serious threat to marine biodiversity, yet many gaps remain in our understanding of the complex processes involved and their societal consequences. Ocean acidification is currently occurring at a geologically unprecedented rate, sub-

jecting marine organisms to an additional, and worsening, environmental stress. Experimental studies show the variability of organisms' responses to simulated future conditions: some are impacted negatively, some positively, and others are apparently unaffected. Furthermore, responses to ocean acidification can interact with other stressors and vary over time, with some potential for genetic adaptation. This complexity of natural processes makes it extremely challenging to assess how future ocean acidification will affect natural marine communities, food webs, and ecosystems, and the goods and services they provide. Nevertheless, substantive environmental perturbations, increased extinction risk for particularly vulnerable species, and significant socio-economic consequences all seem highly likely. Research priorities to reduce the uncertainties relating to future impacts include greater use of natural high-CO₂ analogues, the geological record, and well-integrated observations, together with large-scale, long-term, and multi-factorial experimental studies.

Conclusion

The rate of ocean acidification that we have experienced since pre-industrial times and its projected continuation are "potentially unparalleled in at least the last ~300 million years of Earth history." As such, current ocean acidification represents a new and unprecedented chapter of marine ecosystem change that seems very likely to have a significant impact on marine species and ecosystems (including economically important species), on various industries and communities, and on global food security.

At the Paleo-Eocene Thermal Maximum (56 million years ago), believed to be the closest historical analogue to present-day ocean acidification, geological records indicate that several deep-sea organisms became extinct.

The speed at which ocean acidification is currently happening precludes the option of habitat shifts for many benthic species and may exceed their ability to adapt.

At current rates, aragonite saturation horizons, below which aragonite dissolution occurs, are projected to rise from a few thousand meters to just a few hundred meters, or to the surface, in many ocean regions by the end of the century. If CO₂ emissions continue on a “business as usual scenario,” it is projected that by the end of the century, global mean surface pH will further decrease by ~0.33 units (with H⁺ concentrations more than doubling), and sea surface temperature will increase by 2.7°C, although with considerable regional variability.

Our understanding of ocean acidification and its consequences has increased tremendously in the past 10 years, and research to date, from both laboratory and *in situ* work, has highlighted that organism responses to ocean acidification can be very mixed, even between similar species. This variability reflects that some species may be better adapted for projected future conditions than others; it also highlights that experiment conditions, particularly duration, are important in assessing future long-term responses.

Some general trends are emerging. Ocean acidification will have a negative effect on calcification or growth at different life cycle stages in many key organisms, such as commercial shellfish

and corals, although adequate food supplies may ameliorate some negative responses. Most fish are probably able to maintain sufficient oxygen delivery under predicted future CO₂ levels, but increased CO₂ can have significant impacts upon fish behavior.

Sensitivity to ocean acidification varies at different life stages, so understanding how negative impacts can “carry-over” from larval to adult stages remains a significant challenge. Ocean acidification is generally detrimental to calcifying larvae; non-calcifying larvae

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are more resilient. The impacts of ocean acidification on fertilization success are highly variable, highlighting the potential for selection and genetic adaptation and supporting the concept of “winners and losers” in the face of changing ocean conditions.

Impacts of ocean acidification will be most keenly and rapidly experienced in the Arctic and Antarctic environments due to their low temperatures, affecting saturation state. The Arctic Monitoring and Assessment Program (AMAP) has shown that acidification will not be uniform across the Arctic Ocean. While impacts in that region may be positive for some species, other species may face extinction; furthermore, acidification may contribute to an alteration in the abundance of different fish species, with potential impact upon the livelihoods of local communities.

When considering how ocean acidification will affect human society, the response of tropical coral ecosystems is understandably of great concern—since over 400 million people worldwide live within 100 km of coral reefs, with very many reliant on them for their livelihoods and food security. The fact that over 95% of the world’s calcifying corals currently occur above the saturation horizon, and that coral growth is much reduced near natural CO₂ vents, indicates that in the long-term, it is unlikely to be energetically feasible for corals to grow and thrive below the saturation horizon. Any reduction in coral growth (tropical or cold-water) in the future will have repercussions for the communities that directly or indirectly rely upon them.

Deforestation Fronts

World Wildlife Fund

Introduction

The immediate drivers of deforestation and forest degradation are complex. They include demand for food, fuel, and fiber, but also pollution, human-induced disturbances, and invasive species. Those clearing forests vary from individual families to some of the world's largest corporations. Illegal logging operations target valuable timber, including from protected areas.

Forest degradation creates ecologically simplified, less resilient, and less productive forests. In some countries, these impacts can be more significant than deforestation. Degraded forests en-

This article is adapted from the World Wildlife Fund's Living Forests Report. Content is primarily drawn from Chapter 5, "Saving Forests at Risk." Published in 2015, the complete chapter identifies regions where WWF believes most deforestation is likely to occur between 2010 and 2030, as well as strategies to reverse deforestation. For this adaptation, three regions are highlighted to demonstrate the state and drivers of deforestation. The Living Forests Report is part of an ongoing conversation with WWF partners, policymakers, and business about how to protect, conserve, sustainably use, and govern the world's forests in the 21st century. Complete report chapters are available at http://wwf.panda.org/about_our_earth/deforestation/forest_publications_news_and_reports/living_forests_report/. © World Wildlife Fund for Nature, Gland, Switzerland.

Forest loss/deforestation and degradation are defined by WWF as:

Forest loss/deforestation: Conversion of forest to another land use or significant long-term reduction of tree canopy cover. This includes conversion of natural forest to tree plantations, agriculture, pasture, water reservoirs and urban areas; but excludes logging areas where the forest is managed to regenerate naturally or with the aid of silvicultural measures.

Forest degradation: Changes within forests that negatively affect the structure or function of the stand or site over many decades, and thereby lower the capacity to supply products and/or ecosystem services.

Severe forest degradation: Changes within forests that cause serious and permanent negative changes to the structure or function of the stand or site, and thereby lower the capacity to supply products and/or ecosystem services.

courage invasive species. The bushmeat trade, when unsustainable and/or illegal, respects no laws or boundaries and creates "empty forests" where trees remain but the wildlife is gone. Degradation often begins a slippery slope to deforestation: large canopy gaps can dry out rainforests, leaving them vulnerable to fire; abandoned logging roads provide access to settlers; and authorities are often more willing to grant conversion permits in heavily logged forests.

World Wildlife Fund (WWF) advocates "Zero Net Deforestation and Forest Degradation (ZNDD) by 2020" as a target that reflects the scale and urgency with which threats to the world's forests and climate need to be tackled. Achieving ZNDD will stem the depletion of forest-based biodiversity and ecosystem services, and associated greenhouse gas (GHG) emissions. However, WWF recognizes that achieving ZNDD presents challenges, needs huge political support, and requires great care if it is to be achieved equitably and sustainably while protecting the livelihoods of forest-dependent peoples. It will also re-

quire development of strategies that are environmentally and socially appropriate to national and local contexts.

Deforestation Fronts

The prospect of success in preventing large-scale deforestation will be improved by focusing efforts on those places where threats of deforestation and degradation are greatest. Deforestation fronts are the places where the largest concentrations of forest loss or severe degradation are projected between 2010 and 2030, under business-as-usual scenarios and without interventions to prevent losses. Collectively, these places will account for over 80% of the forest loss projected globally by 2030, i.e. up to 170 million ha. So, which forests are on the firing line, and what is driving deforestation? The following three regions provide a sample of the world's deforestation fronts.

Amazon

The Amazon is a complex natural region, comprising an array of interdependent ecosystems. It is hugely important in terms of the ecosystem services it provides, including ecological processes, biodiversity, and cultural diversity.

Since 2005 there has been an important reduction in the rate of deforestation across parts of the Amazon region but deforestation and forest degradation continue at an alarming rate, threatening to overturn gains that have been made. The Amazon is the biggest deforestation front in the world, according to WWF projections, and interventions are urgently needed to prevent a large-scale, irreversible ecological disaster.

Forest losses from 2001 to 2012 averaged 1.4 million ha per year for the Amazon biome, resulting in a total loss of 17.7 million ha in those 12 years. Brazil was responsible, on average, for 75% of accumulated deforestation, with Brazil, Peru, and Bolivia together accounting for 90%.

Recent WWF estimates suggest that 27% of the Amazon biome will be without trees by 2030, 13% from new deforestation, if the average deforestation rate for the last 10 years for each country continues. This would give a total area lost to deforestation from 2010 to 2030 of 23 million ha. If construction goes ahead on planned hydroelectric dams and major new paved roads—such as the Carretera Marginal de la Selva, running from Peru through Ecuador to Colombia; the Trans-Amazon highway; the Manaus-Porto Velho “BR 319”; and the Cuiabá-Santarem “BR 163”—coupled with the new Interoceanic Highway running through Brazil, Bolivia, and Peru, deforestation could double to 48 million ha between 2010 and 2030, or 100 million by 2050.

The Andean-Amazon deforestation area—spanning 670 million ha from Colombia to Bolivia—includes sub-fronts moving in from the southeast,

Brazil and Bolivia, the Andean piedmont, and from the north in Colombia and Ecuador. Deforestation has been growing particularly in the Andean-Amazon countries, namely Peru—due to expansion of palm oil, agriculture, il-

Though the deforestation rate in Brazil has decreased, changes to the Forest Code in 2012 have been associated with increased deforestation.

legal logging and informal mining—parts of Bolivia, Colombia and, to a lesser degree, Venezuela, Guyana, Suriname, and French Guiana. Though the deforestation rate in Brazil has decreased, changes to the Forest Code in 2012 have been associated with increased deforestation, including within the Amazon biome.

The primary causes of forest loss and/or severe degradation in this region include the following. **Pasture and cattle ranching** is the dominant cause in many areas and is also linked to land speculation in some countries. The expansion of **mechanized agriculture**, particularly for animal feed and biofuels, using soy, oil palm, and corn, is a key cause, with increased production linked to subsidized resettlements in some countries. **Indirect land-use change** can be significant, e.g. if soy replacing pasture results in cattle rearing moving into natu-

 Deforestation front	 Projected loss (million ha) 2010 to 2030
Amazon	23-48
Atlantic Forest/Gran Chaco	10
Borneo	22
Cerrado	15
Chocó-Darién	3
Congo Basin	12
East Africa	12
Eastern Australia	3-6
Greater Mekong	15-30
New Guinea	7
Sumatra	5
Total from 11 deforestation fronts	127-170

ral forests. **Small-scale agriculture** is expanding in regions such as northern and eastern Bolivia, Colombia, Ecuador, Peru, and the Guianas, where high levels of poverty, pressure for land, unsustainable practices, and problems of control are leading to an expansion.

Dams and hydropower expansion, including settlement around dams and associated infrastructure, is a major driver behind deforestation. The area at risk from deforestation impact occurs between 40-100 km from hydroelectric dams. There are 154 constructed dams, and another 298 either under construction or planned in the Amazon biome. Dam impacts often overlap with protected areas and indigenous territories.

Roads give access to remote areas, bringing people and land speculation inwards. Mechanisms to manage or reduce the impacts of new roads are often absent or poorly implemented. The fronts showing the greatest deforestation rates are areas with more roads, showing a strong correlation between the two. Nearly 95% of deforestation in Brazil Amazon was found to be within 5.5 km of road and 1 km of navigable rivers.

Important secondary causes of forest loss and/or severe degradation include **forest fires** due to poorly controlled burning for land clearance and management. In addition, road development accompanies mines and oil and gas drilling, often increasing deforestation. Mining is significant in places such as Peru, where artisanal and small-scale alluvial **gold mining** has increased 400% since 1999.

Finally, the **unsustainable legal and illegal timber trade** contributes to forest degradation and can be the first stage of forest conversion, although this is a less important cause.

Congo Basin

The Congo Basin contains 20% of the world's tropical forests—some 301 mil-

lion ha—and makes up one of the most important wilderness areas left on Earth. A mosaic of rivers, forests, savannahs, swamps, and flooded forests, the Congo Basin forests span six countries—Cameroon, Central African Republic, Democratic Republic of Congo (DRC), Republic of the Congo, Equatorial Guinea, and Gabon—are home to species such as mountain and lowland gorillas, bonobos, okapis, chimpanzees, and elephants.

Change is sporadically coming to the Congo basin, influenced by politics and economics in individual countries. De-

Population in Congo Basin countries is expected to double between 2000 and 2030, leading to 170 million people concentrated mainly in urban areas, threatening forests close to large cities.

forestation is less a *front* than many individual *incursions*, and has proceeded more slowly than in other fronts. Losses were estimated as 0.19% from 1990 to 2000, and 0.14% from 2000 to 2010, with forest decreasing everywhere. Deforestation rates are thus historically low, but some estimates show degradation is an increasing problem and is generally under-reported. DRC has the highest deforestation, 6-7 million ha since 2000, followed by Cameroon and Equatorial Guinea.

Drawing on published analysis, WWF estimates that a minimum of 12 million ha are likely to be lost by 2030,

with forests retreating to a core and contiguous forest fragmenting into three areas: one between Gabon, Cameroon, and the Republic of Congo, and one each in eastern and western DRC. However, volatile politics and nervous investors make future projections difficult. A series of national and regional conflicts have resulted in many refugees, which can increase or decrease overall rates of forest loss. Moreover, population in Congo Basin countries is expected to double between 2000 and 2030, leading to 170 million people concentrated mainly in urban areas, threatening forests close to large cities.

The leading cause of deforestation in the region is small-scale agriculture, primarily **shifting cultivation**. Some of the forest returns during fallow periods, making overall deforestation hard to estimate. In addition, **fuelwood** comprises an estimated 90% of timber harvest in the Congo Basin. Large **agricultural plantation development** is likely to become more important, including for **palm oil**. Since 2009, 1.6 million ha of palm oil projects have been announced, with four companies currently trying to secure 180,000 ha for palm oil in southern Cameroon, and large projects planned in DRC, including a Chinese company seeking 1 million ha for oil palm development. **Rubber** and **soy** are also gaining importance.

Much of the **timber industry** in this region is inefficient, and some probably unsustainable. Illegal logging is suspected to be widespread, accounting for up to half the timber extraction. Illegally logged timber is mainly going to China but some goes to the EU despite the existence of controls. If the region experiences significant economic growth, the domestic market could also put pressure onto forest resources.

Large-scale mining, mainly by Chinese and Australian companies, and **artisanal mining** are both important. The latter is often in protected areas. Mining permits sometimes overlap with conser-

vation areas. For example, over 120 exploration permits have been issued in Cameroon in the last two years with overlapping conservation and mining permits, and the nature of operations in DRC has also caused concern.

Population increase and infrastructure development are important secondary causes of deforestation. Rising population is leading to expansion of urban areas and threatening forests close to large cities and in other development areas. Realization of currently planned and funded transport infrastructure in the region is projected to increase deforestation threefold.

Finally, **cattle** may become more significant if the climate becomes drier as projected, although ranching is currently constrained by tsetse fly.

Greater Mekong

The Greater Mekong region encompasses the countries of Cambodia, Lao People's Democratic Republic (Laos), Myanmar, Thailand, and Vietnam. The economies in the region are booming, but with this comes the complex task of balancing legitimate needs for development while safeguarding forest ecosystems and ecosystem services.

Before the 1970s, most of the Greater Mekong was highly forested. However, today, most of the region's natural forests have been reduced, severely fragmented, or degraded, including from the impacts of wars. Only about half of the Greater Mekong land area is currently forested, with only 13% of primary forests remaining. This, alongside poaching and wildlife trade, is creating a biodiversity crisis. Primary forest has virtually disappeared in Vietnam, is extremely low in Cambodia, and scarce in Laos, Myanmar, and Thailand. Natural regeneration and plantation establishment in China and Vietnam has recovered some area under trees, but not natural forest.

Between 1973 and 2009, forests in the Greater Mekong declined by almost a third: 43% in Vietnam and Thailand; 24% in Laos and Myanmar; and 22% in Cambodia. Intact forest area was reduced from 70% to 20% of the region, leaving around 98 million ha of forest. Mangroves have been severely affected, partly by wartime defoliants, with the Lower Mekong countries losing an estimated 222,650 ha between 1980 and 2005. Illegal logging, including in protected areas, is a major problem in Cambodia, Myanmar, and Laos, but prevalent throughout the region.

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WWF projects further losses of 15-30 million ha by 2030, with only 14% of remaining forest consisting of core, intact areas. Losses are likely to remain highest in Cambodia, Laos, and Myanmar, where 2010-2020 deforestation is projected at 4.8 million ha. A critical cause amplifying deforestation pressures is weak governance, anarchic development, and economic dependence on natural resources.

Conversion of forest for **crop plantations** and **agriculture**, namely **sugar, rice, rubber, and biofuels**, is a key cause of deforestation in the region. In

Myanmar alone, over 2 million ha of forest have been allocated to agriculture; between 2011 and 2013, 1.15 million ha of primary forest was cleared each year for timber production and conversion to agriculture.

Rapid development of roads and infrastructure lead to **new settlements** that encroach on forest for small-scale agriculture development. Additionally, legal and policy restrictions on logging in Vietnam, China, and Thailand, coupled with **growing demand**, are driving unsustainable and **illegal logging** for export and indirect land-use change in Cambodia, Laos, and Myanmar. Illegal logging, including within protected areas, is prevalent throughout the region.

Conclusion

Reversing deforestation fronts will require measures to remedy the fundamental market and governance failures that drive poor land-use choices and practices. Land-use decisions are influenced by many actors: property owners or communities with land or resource access rights deciding how to use their land; governments shaping economic policies, regulations, and spatial plans; investors assessing the risk and return of a business activity in a given place; corporations managing global supply chains and anticipating market trends; and consumers deciding what to buy or which politicians to elect.

Coherent and fair incentives to maintain the integrity of forest ecosystems will need to integrate these diverse interests and actors and shape the myriad systems influencing land-use choices. Systemic, integrated approaches to improved land-use decision-making are needed both in specific places and in global supply chains.

News and Announcements

Renewable Natural Resources Foundation

Round Table Meeting on Toxic Substances Control Act

The RNRF Washington Round Table on Public Policy met with Dr. Richard Denison, a lead senior scientist with Environmental Defense Fund (EDF), in Washington, D.C. on December 9, 2015. Denison discussed the history of the Toxic Substances Control Act (TSCA) and recent activity surrounding legislative reform.

Congress enacted TSCA in 1976 to address the production, importation, use, and disposal of chemicals. TSCA is the United States' main chemical safety legislation, covering most chemicals used in industry and in commercial and consumer products. It is meant to give the Environmental Protection Agency (EPA) the authority to review most new chemicals under development, as well as the power to regulate chemicals already in or entering commerce if they present an "unreasonable risk" to human health or the environment.

However, TSCA is ineffective, hindering both EPA's ability to generate information and its ability to act on that information when it indicates significant risk. EPA has required testing for less than 300 chemicals in 39 years, while tens of thousands of industrial chemicals already in commerce were grandfathered in and granted a strong "presumption of innocence." Of the 300 chemicals tested, only 5 have been regulated because of the extraordinarily high hurdles EPA faces for testing and regulation. Legislation was introduced to reform TSCA in 2015.

The Frank R. Lautenberg Chemical Safety for the 21st Century Act (S. 697) was introduced on March 10, 2015, with Senators Udall and Vitter as its main sponsors. The Senate passed S. 697 on December 17, 2015. H.R. 2576, which passed through the full House on a 398-1 vote, is a far more skeletal reform of TSCA, generally avoiding any highly controversial changes to the existing TSCA.



Richard Denison

S. 697 generally improves many aspects of the current TSCA, including establishing a lower hurdle for EPA to require testing, requiring an affirmative finding of safety by the EPA, mandating the EPA to conduct safety assessments and determinations for all high-priority chemicals, making chemical information more available to states and health professionals, and preventing the EPA from taking costs and other factors into consideration when making safety assessments.

Although the current TSCA is so ineffective that almost any change is seen as an improvement, S. 697 presents an imperfect reform. The most contentious aspect is federal preemption of state authority over chemical regulation. Favored by industry, preemption in S. 697 is much more extensive than under current TSCA. Organizations such as the Environmental Working Group (EWG) and the Center for Environmental Health cite preemption of state action as a flaw in the bill. Under S. 697, states are preempted from taking new actions to regulate any chemical for which EPA has initiated a safety review, and final actions by EPA generally preempt states. EPA's safety review and regulation process could take more than seven years, blocking state action in the meantime. In addition, states would be prevented from adopting and co-enforcing EPA's chemical regulations.

American Geophysical Union

AGU Fall Meeting Location Change

AGU has announced that its annual Fall Meeting, an event that regularly attracts more than 25,000 Earth and space scientists and other participants from around the world, will move to New Orleans in 2017 and to Washington, D.C. in 2018.

Meetings Information

Visit <http://www.rnrf.org/> for a list of meetings relevant to natural resources and environmental policy and management. Submit meeting notices to info@rnrf.org.

For nearly 50 years, the AGU Fall Meeting has been held in San Francisco. During that time, it has grown from a gathering of a few hundred researchers to the largest Earth and space science event in the world. The meeting will remain in San Francisco in 2016, and plans are underway to return to the City by the Bay in 2019.

For more information, contact AGU, 2000 Florida Avenue NW, Washington, DC 20009; (202) 462-6900. www.agu.org.

American Meteorological Society

Milestones for the AMS Education Program

In a milestone year for the now 25-year-old AMS Education Program, one of the proudest achievements was the successful completion of the five-year AMS Climate Studies Diversity Project. This NSF-funded initiative introduced and enhanced geoscience and/or sustainability teaching at nearly 100 minority-serving institutions (MSIs) since 2011.

Since 2001, in faculty enhancement through the AMS Weather Studies and Ocean Studies courses and now the Climate Studies Diversity Project, AMS has engaged 24,000 students through 220 MSIs.

For more information, contact AMS, 45 Beacon Street, Boston, MA 02108; (617) 227-2425. www.ametsoc.org.

American Society of Civil Engineers

Sustainability Summit

ASCE's Sustainability Summit, held January 7-9, 2016, sent a clear message that the world needs the help of civil engineers. This call to action captured the tremendous opportunity in front of civil engineers, while also presenting a

daunting challenge. The concept of building infrastructure in a sustainable manner amid unprecedented environmental unpredictability requires a sea change within the industry.

Discussions included how to create greater urgency to adopt sustainability practices, tangible measures of success, and financial updates of sustainable engineering. Leadership and the civil engineer's role in driving sustainable solutions was a major topic at the Summit. Leadership increasingly means working to serve the complete project.

For more information, contact ASCE, 1801 Alexander Bell Drive, Reston, VA 20191; (800) 548-2723. www.asce.org.

American Society of Landscape Architects

Case Studies of Sustainable Landscape Design

ASLA announced a newly expanded version of its "Designing Our Future: Sustainable Landscapes" online exhibition that highlights real-world examples of sustainable landscape design and its positive effects on the environment and quality of life. These spaces use natural systems to provide ecosystem services, transform untapped assets into vital community spaces, and create new economic opportunities. They ultimately provide significant environmental, social, and economic value.

Ten new case studies that range from a coastal ecological restoration project to a volunteer-run urban farm illustrate just what sustainable landscapes are and how they provide important benefits on a variety of scales.

The new case studies were carefully selected to show a diversity of landscape types and scales and reflect geographical diversity. There are now a total of 40 case studies.

For more information, contact ASLA, 636 Eye Street, NW, Washington, DC 20001; (202) 898-2444. www.asla.org.

American Water Resources Association

2016 Spring Specialty Conference

AWRA's 2016 Spring Specialty Conference will take place in Anchorage, AK from April 25-27, 2016. The theme of the meeting is Water, Energy, and Environment. Alaska represents a microcosm of the challenges and problems facing the other 49 states and other countries: the development of water and energy infrastructure in villages; integrated water-energy systems in Anchorage; and extensive oil, gas, and coal development. Join AWRA for discussions on the latest advances, case studies, challenges, and solutions to water, energy, and environmental issues.

For more information, contact AWRA, P.O. Box 1626, Middleburg, VA 20118; (540) 687-8390. www.awra.org.

Geological Society of America

Science Organizations Thank Appropriators

GSA joined members of the Coalition for Aerospace and Science to thank appropriators for increasing NASA funding for FY2016. The Commerce Justice, Science, and Related Agencies division of the FY2016 appropriations bill included a 7.1% increase to NASA's total budget. This increased funding will be important to ensuring the success of ongoing investigations and enabling exciting new missions and research while growing the economy and inspiring the next generation of scientists and engineers. It is also crucial to maintaining the United States' long-standing global leadership in space exploration and scientific discovery.

For more information, contact GSA, P.O. Box 9140, Boulder, CO 80301; (303) 357-1806. www.geosociety.org.

Society of Environmental Toxicology and Chemistry

Advancing the Adverse Outcome Pathway Concept

SETAC is initiating a horizon scanning effort to advance the science and application of the Adverse Outcome Pathway (AOP) framework. This approach will allow SETAC to identify and begin to address recognized, ongoing, and remaining issues relevant to the application of the AOP framework to chemical risk assessment in the context of human and ecological health. SETAC is asking members of the global scientific community to propose questions that consider key outstanding or limitations that must be addressed in order to realize the full potential of the AOP framework in research and regulatory decision-making. Questions can be submitted through June 30, 2016.

For more information, contact SETAC, 229 S. Baylen Street, Pensacola, FL 32502; (850) 469-1500. www.setac.org.

Society of Wood Science and Technology

2017 IUFRO Forest Products Conference

The 2017 International Union of Forest Research Organizations (IUFRO) Conference will take place from June 12-16, 2017 in Vancouver, BC. In recognition of the pressing global need for the forest sector to be a leader in sustainability, diversification, and innovation, the theme of the conference is "Forest Sector Innovations for a Greener Future."

For more information, contact SWST, P.O. Box 6155, Monona, WI 53716; (608) 577-1342. www.swst.org.

International News

World Health Organization

An estimated 12.6 million deaths each year are attributable to unhealthy environments

An estimated 12.6 million people died as a result of living or working in an unhealthy environment in 2012—nearly 1 in 4 of total global deaths, according to WHO. Environmental risk factors such as air, water and soil pollution; chemical exposures; climate change; and ultraviolet radiation contribute to more than 100 diseases and injuries.

Noncommunicable diseases (NCDs) contribute to largest share of environment-related deaths. The second edition of the report, *Preventing disease through healthy environments: a global assessment of the burden of disease from environmental risks*, reveals that since the report was first published a decade ago, deaths due to NCDs, mostly attributable to air pollution (including exposure to second-hand tobacco smoke), amount to as much as 8.2 million of these deaths. NCDs, such as stroke, heart disease, cancers, and chronic respiratory disease, now amount to nearly two-thirds of total deaths caused by unhealthy environments.

Deaths from infectious diseases, such as diarrhea and malaria, often related to poor water, sanitation and waste management, have declined. Increases in access to safe water and sanitation have been key contributors to this decline, alongside better access to immunization, insecticide-treated mosquito nets, and essential medicines.

"A healthy environment underpins a healthy population," says Dr. Margaret Chan, WHO Director-General. "If countries do not take actions to make environments where people live and work healthy, millions will continue to become ill and die too young."

The report emphasizes cost-effective measures that countries can take to reverse the upward trend of environment-related disease and deaths. These include reducing the use of solid fuels for cooking and increasing access to low-carbon energy technologies.

"There's an urgent need for investment in strategies to reduce environmental risks in our cities, homes and workplaces," said Dr. Maria Neira, WHO Director, Department of Public Health, Environmental and Social Determinants of Health. "Such investments can significantly reduce the rising worldwide burden of cardiovascular and respiratory diseases, injuries, and cancers, and lead to immediate savings in healthcare costs."

Environmental risks take their greatest toll on young children and older people, the report finds, with children under 5 and adults aged 50 to 75 years most impacted. Yearly, the deaths of 1.7 million children under 5 and 4.9 million adults aged 50 to 75 could be prevented through better environmental management. Lower respiratory infections and diarrheal diseases mostly impact children under 5, while older people are most impacted by NCDs.

Regionally, the report finds, low- and middle-income countries in the WHO South-East Asia and Western Pacific Regions had the largest environment-related disease burden in 2012, with a total of 7.3 million deaths, most attributable to indoor and outdoor air pollution.

Low- and middle-income countries bear the greatest environmental burden in all types of diseases and injuries. However, for certain NCDs, such as cardiovascular diseases and cancers, the per capita disease burden can also be relatively high in high-income countries.

The report cites proven strategies for improving the environment and preventing diseases. For instance, using clean technologies and fuels for domestic cooking, heating, and lighting would

reduce acute respiratory infections, chronic respiratory diseases, cardiovascular diseases, and burns. Increasing access to safe water and adequate sanitation and promoting hand washing would further reduce diarrheal diseases.

Tobacco smoke-free legislation reduces exposure to second-hand tobacco smoke, and thereby also reduces cardiovascular diseases and respiratory infections. Improving urban transit and urban planning and building energy-efficient housing would reduce air pollution-related diseases and promote safe physical activity.

Many cities around the world are already implementing many of these cost-effective measures. Curitiba, Brazil has invested heavily in slum upgrading, waste recycling, and a popular “bus rapid transit” system which is integrated with green spaces and pedestrian walkways to encourage walking and cycling. Despite a five-fold population increase in the past 50 years, air pollution levels are comparatively lower than in many other rapidly growing cities and life expectancy is 2 years longer than the national average.

Through WHO’s water safety plans, which work to identify and address threats to drinking-water safety, Amarpuri, Nepal identified open defecation as a water quality hazard contributing to diseases in the area. As a result, the village built toilets for each household and was later declared an Open Defecation Free Zone by the local government.

Currently, WHO is working with countries to take action on both indoor and outdoor air pollution. At the World Health Assembly in May, WHO will propose a road map for an enhanced global response by the health sector aimed at reducing the adverse health effects of air pollution.

For more information, visit <http://www.who.int/mediacentre/news/releases/2016/deaths-attributable-to-unhealthy-environments/en/>.

International Institute for Sustainable Development

International Day of Forests Celebrates Forests and Water

Focusing on the multiple links between forests and water systems, the International Day of Forests was celebrated on March 21 around the globe. The Day aims to highlight the role of forests in supplying most of the world’s accessible freshwater as well as building and strengthening resilience, especially to the impacts of climate change.

In his message, UN Secretary-General Ban Ki-moon underlined that the world’s forests are essential to realizing a shared vision for people and the planet, and central to the future prosperity and the stability of the global climate. He called on governments and partners to adopt holistic policies and practices to protect, restore, and sustain forests.

Seven key messages are being promoted to make the Day. They include:

- Forested watersheds and wetlands supply 75% of the world’s accessible freshwater for domestic, agricultural, industrial, and ecological needs.
- About one-third of the world’s largest cities obtain a significant proportion of their drinking water directly from forested protected areas.
- The water security of nearly 80% of the world’s population is threatened.
- Forests act as natural water filters.
- Climate change is altering forests’ role in regulating water flows and influencing the availability of water sources.
- Improved water resource management can show considerable economic gains.
- Forests have a crucial role in building and strengthening resilience.

In a statement marking the Day, Executive Secretary of the Convention on Biological Diversity (CBD) Braulio Dias noted that forests are crucial to the sustainable management of water ecosystems and resources, and that water is essential for the sustainability of forest ecosystems. Noting that the links are inseparable, he called for a greater understanding and appreciation of the value of forests and the ecosystem services they provide to enable decision makers to better assess the trade-offs associated with alternatives for land and water use.

Also for the Day, the International Tropical Timber Organization (ITTO) highlighted that tropical forests provide crucial environmental services, and that there is strong evidence that sustainable forest management can protect water catchments, thereby helping to maintain downstream water quality, reducing flooding and sedimentation, and contributing to local livelihoods.

For more information, visit <http://nr.iisd.org/news/international-day-of-forests-celebrates-forests-and-water/>.

RENEWABLE RESOURCES JOURNAL

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