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Chapter 6
Helping Mother Earth Heal: Diné College and Enhanced Natural Attenuation Research at U. S. Department of Energy Uranium Processing Sites on Navajo Land

William J. Waugh, Edward P. Glenn, Perry H. Charley, Marnie K. Carroll, Beverly Maxwell, and Michael K. O'Neill

Contents

Abstract Diné College is a key stakeholder and partner with the U.S. Department of Energy in efforts to develop and implement sustainable and culturally acceptable remedies for soil and groundwater contamination at uranium mill tailings processing and disposal sites on Navajo Nation land. Through an educational philosophy grounded in the Navajo traditional living system which places human life in harmony

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with the natural world, the College has helped guide researchers to look beyond traditional engineering approaches and seek more sustainable remedies for soil and groundwater contamination at former uranium mill sites near Monument Valley, Arizona, and Shiprock, New Mexico. Students and researchers are asking first, what is Mother Earth already doing to heal a land injured by uranium mill tailings, and second, what can we do to help her? This guidance has led researchers to investigate applications of natural and enhanced attenuation remedies involving native plants – phytoremediation, and indigenous microorganisms – bioremediation. College faculty, student interns, and local residents have contributed to several aspects of the pilot studies including site characterization, sampling designs, installation and maintenance of plantings and irrigation systems, monitoring, and data interpretation. Research results look promising.

6.1 Introduction

With bright yellow cottonwood canopies illuminating the San Juan River floodplain below, students from Diné College, a Navajo-owned community college, gather in a fenced plot on an ancient river terrace in Shiprock, New Mexico, armed with tape measures and pruners to record the growth of native phreatophytes and clip stems and leaves for chemical analysis. Phreatophytes – literally, "well plants" – survive in this desert environment by extending their roots down like straws to suck groundwater. As students work on an autumn day in 2008, a film crew from the National Science Foundation interviews some of their peers and instructors for the documentary, "Weaving STEM (science, technology, engineering, and mathematics) Education and Culture: The Faces, Places, and Projects of the Tribal Colleges and Universities Program." Curriculum in the Diné Environmental Institute (DEI) at the College is designed to weave environmental science methods with Navajo cultural traditions – Navajo Science.

The students, their instructors, and scientists from the U.S. Department of Energy (DOE), University of Arizona, and New Mexico State University have teamed up on a phytoremediation research project. Phytoremediation is the name given to the science and practice of using plants as part of the remedy for contaminated soil and groundwater. An objective of the research is to determine if the native phreatophytes can be grown to withdraw groundwater and slow the spread of contamination away from a nearby uranium mill tailings disposal site, and do so without contaminating the plants.

Phytoremediation, a type of enhanced natural attenuation, fits well with the College's approach for weaving Navajo culture into environmental science education. Navajo tradition teaches us that we are connected to the land, that we should live in harmony with Mother Earth. By teaming with the DEI and incorporating the goals of Navajo Science, DOE is learning to take a more holistic approach in developing remedies for contamination related to past uranium milling on Navajo land. Phytoremediation, bioremediation, and enhanced natural attenuation are scientific approaches that ask, allegorically, "What is Mother Earth already doing to heal a land injured by uranium mill tailings, and what can we do to help her?"

As future scientists and community leaders, today's Diné College students are living a new chapter in a Navajo story about uranium mining, milling, and the U.S. Government. Many of these students' grandfathers and community elders, when they were young, moved their families to far corners of the Navajo Nation to work in mines and mills that had sprung up across the Colorado Plateau to supply uranium to fuel the weapons of the Cold War. These families were not forewarned that the colorless, odorless radon gas, which emanates from the uranium ore and mill tailings, would eventually cause lung cancer among the Navajo miners at a rate 20–30 times higher than that of nonminers in the region, a tragedy that continues to impact their families and communities even today.

This chapter serves as an example of how Native American students and their way of life can be incorporated into an ongoing remediation and research project to better understand how to restore Mother Earth. It provides an overview of the environmental legacy of Cold War uranium mining and milling, of efforts by the U.S. Congress and federal agencies to repair and provide long-term care of land and water contaminated by uranium milling, and of the role Diné College students and faculty are playing as stakeholders and researchers, in collaboration with students and researchers from the University of Arizona, New Mexico State University, and the U.S. DOE, to discover and enhance natural remedies for cleaning up soil and groundwater at uranium mill tailings sites on Navajo land near Monument Valley, Arizona, and Shiprock, New Mexico.

6.2 Uranium Mill Tailings: A Cold War Legacy

Uranium mill tailings are residues of crushed ore following extraction of uranium oxide, commonly called yellowcake. After a sequence of grinding, separating, and concentrating uranium oxide during the milling process, most of the original ore is discarded as tailings and other residual wastes. Almost all of the uranium oxide processed in the United States during the mid 1900s, including that unearthed on Navajo Land, was purchased by the U.S. Government to fuel the massive Cold War weapons production effort. Federal purchasing of uranium triggered a mining boom in the Four Corners states of Utah, Colorado, Arizona, and New Mexico, as prospectors equipped with radiation detectors combed the sandstone outcrops in the region. By 1955, there were hundreds of mines producing high-grade ore and several AEC-funded milling facilities and buying stations operating on the Colorado Plateau. The uranium mining and milling boom abated in 1962 with a drop in AEC purchases of uranium, and then nearly ceased altogether in 1970 when the AEC stopped purchasing uranium. Many mines and mills were abandoned, leaving a legacy of tailings and processing residues that can adversely affect human and environmental health.

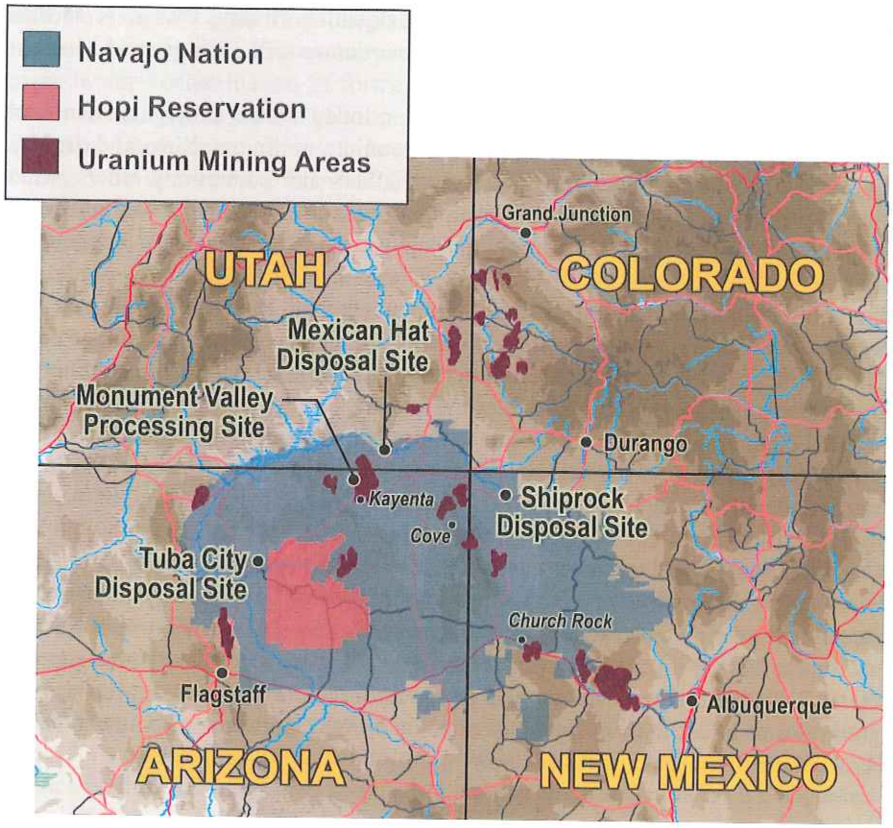

Fig. 6.1 Map of the Navajo Nation showing uranium mining areas and uranium mill tailings sites managed by the U.S. Department of Energy under the Uranium Mill Tailings Radiation Control Act of 1978

6.2.1 *Navajo Uranium Mining, Milling and Health Effects*

The Navajo Nation, covering about seven million hectares (over 27,000 square miles) of the Colorado Plateau in northeastern Arizona, northwestern New Mexico, and southeastern Utah, played a major role in the Cold War uranium mining boom. Between 1943 and 1945, the Manhattan Project, a secret U.S. military project instituted during World War II to develop the first atomic bomb, recovered approximately 34,000 kg (about 76,000 pounds) of uranium oxide from vanadium mill tailings on Navajo land (Chenoweth 1997). Navajos and other Native Americans guided prospectors and miners to large deposits of uranium-bearing ore on reservation land (Johnston et al. 2007). Discoveries of uranium, first near Cove, Arizona (Brugge and Goble 2006), and then elsewhere on Navajo land, eventually led to the development of mining and milling regions near Shiprock, New Mexico; Church Rock, New Mexico; Monument Valley, Arizona; and Kayenta, Arizona (Fig. 6.1). Unaware of the health risks posed to miners, millers, and local residents, the Navajo Tribal Council endorsed these private contracts because of the employment opportunities they created for Tribal members (Johnston et al. 2007).

After many years of epidemiology studies showing much higher rates of lung cancer and other diseases in Navajo miners than in the general population of the region (Gilliland et al. 2000; Brugge and Goble 2002) and after years of thwarted efforts by Navajos and their advocates to seek restitution from the federal government, the Radiation Exposure Compensation Act (RECA) was passed by the U.S. Congress and signed into law in 1990. The RECA states that the government "offers an apology and monetary compensation to individuals who contracted certain cancers and other serious diseases … following their occupational exposure to radiation while employed in the uranium industry during the build-up to the Cold War." The RECA Amendment of 2000 "broadened the scope of eligibility for benefits … to include uranium mill workers and uranium ore transporters and adding compensable diseases, thus allowing more individuals to be eligible to qualify."

Given this history, Navajo people often perceive uranium as a monster, as described here by Yazzie-Lewis (2006). "The Navajo word for monster is *nayee*. The literal translation is 'that which gets in the way of a successful life.' Navajo people also believe that one of the best ways to start to overcome or weaken a monster as a barrier to life is to name it. Every evil—each monster—has a name. Uranium has a name in Navajo. It is *leetso*, which means 'yellow brown' or 'yellow dirt.' Aside from its literal translation, the word carries a powerful connotation. Sometimes when we translate a Navajo word into English, we say it 'sounds like' something. We think *leetso* sounds like a reptile, a monster."

6.2.2 *Uranium Mill Tailings Radiation Control Act*

The United States Congress enacted the regulatory framework for cleanup, containment, and long-term care of uranium mill tailings with passage of the Uranium Mill Tailings Radiation Control Act (UMTRCA) in 1978. The fundamental purpose of this legislation was to mitigate health risks to the public, in perpetuity and in an environmentally sound manner, from residual radioactive materials related to processing of uranium ore. The act authorized the U.S. Environmental Protection Agency (EPA) to issue standards for cleanup and long-term management of uranium mill tailings including standards for remedial action, groundwater quality, and performance of tailings containment systems called disposal cells. The EPA standards were promulgated in 40 Code of Federal Regulations (CFR) 192, "Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings."

UMTRCA designated the U.S. Nuclear Regulatory Commission (NRC) as the agency responsible for enforcing the EPA standards and assigned the responsibility for cleanup, remediation, and long-term care of tailings sites to DOE. It required the NRC to evaluate the design and implementation of remedies by DOE and, after remediation, to concur that remedies satisfy the standards developed by EPA. DOE, as licensee to the NRC for long-term care, is responsible for site inspections, monitoring, reporting, and record keeping. After receipt of an NRC license, sites located on Tribal land revert to Tribal control. Tribes generally allow DOE to fulfill its custody and long-term care responsibilities through a site access agreement.

6.2.3 U.S. Department of Energy and Long-Term Stewardship

DOE created the Office of Legacy Management (DOE-LM) in 2003 to function as the Federal licensee to NRC for long-term care of UMTRCA sites (http://www.lm.doe.gov). The accepted remedy was to contain tailings and other residual contamination from the milling operation in an engineered, near-surface disposal cell designed to limit radon escape into the atmosphere, limit percolation of rainwater into tailings – and subsequent leaching of contaminants into groundwater – and continue limiting radon and water flux for 200 to 1,000 years. If former uranium processing activities contaminated groundwater at a particular site, the NRC general license pertains only to the surface remediation; NRC will not fully license the site until groundwater quality satisfies applicable EPA standards.

UMTRCA sites are generally located in the vicinity of uranium ore deposits in arid and semiarid regions of Western states. Four sites are located on Navajo land: the Mexican Hat Disposal Site in southeastern Utah, the Shiprock Disposal Site in northwestern New Mexico, and the Monument Valley Processing Site and Tuba City Disposal Site, both in northeastern Arizona (Fig. 6.1).

6.3 Helping Mother Earth Heal: Navajo Tradition and Science

Navajo cultural tradition teaches the Diné (Navajo for 'child of the Holy People') to fulfill their duty as caretakers of Mother Earth; to reciprocate her nurturing by helping her restore and maintain the health of a desert land. Putting this into practice, Diné College students, together with students and researchers from the University of Arizona, New Mexico State University, and funded by DOE-LM, are exploring natural remedies for groundwater contamination at the Monument Valley Processing Site and the Shiprock Disposal Site. This section provides a brief history of Diné College, a Navajo-owned college on the Navajo Nation, and describes how an educational policy instituted by the College has helped to shape DOE's research approaches at Monument Valley and Shiprock, and to focus on natural and enhanced attenuation (EA) remedies.

6.3.1 Diné College and Sá'ah Naagháí Bik'eh Hózhóón

Diné College was founded in 1968 as the first nonprofit public institution of higher learning established by Native Americans for Native Americans (http://www.dinecollege.edu). Formerly Navajo Community College, Diné College is the

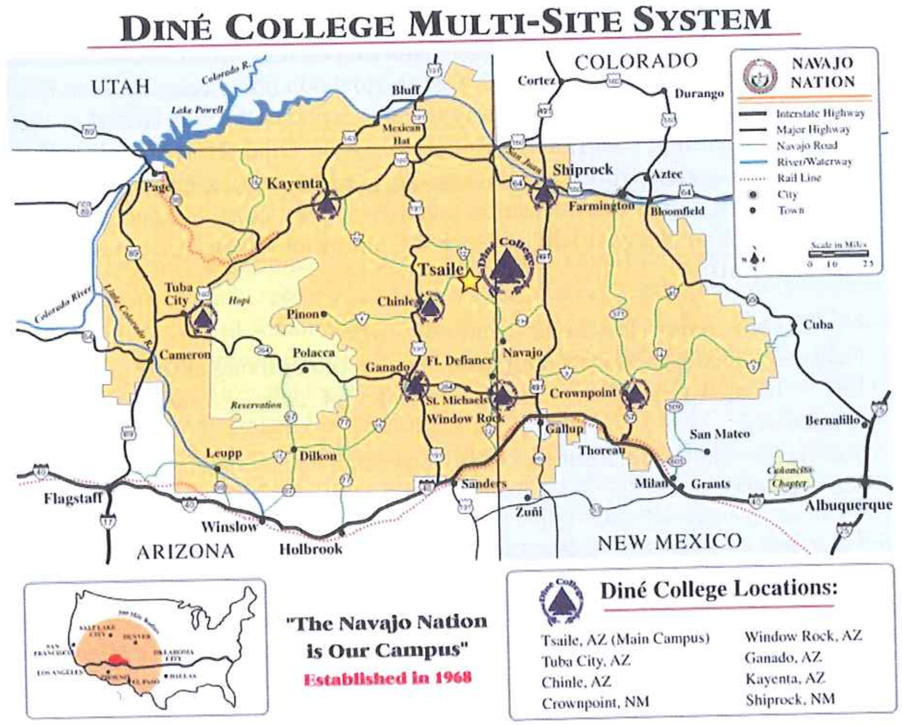

Fig. 6.2 Diné College campus locations on the Navajo Nation

oldest Tribally controlled college in the United States, with eight campuses and centers in Arizona and New Mexico (Fig. 6.2). The main residential campus at Tsaile, Arizona, with buildings designed in the tradition of the Navajo Hogan, adorns the flanks of the Chuska Mountains near the eastern, upper end of Canyon De Chelly National Monument.

Diné College was chartered by the Navajo Nation as the "Higher Education Institution of the Navajo." The College currently enrolls over 2,000 students each semester. The College is accredited by the Higher Learning Commission and is a member of the North Central Association of Colleges and Schools. The landmark decision by the Navajo Nation to create a Tribally owned, postsecondary institution set the precedent for subsequent establishment of several community colleges owned and operated by Native Americans on or near other reservations in the United States. Diné College is one of the founding members of the American Indian Higher Education Consortium, which now represents 33 Tribal colleges and universities.

In creating an institution of higher learning, the Navajo Nation sought to encourage Navajo youth to become contributing members of both the Navajo traditional community and the greater world community. To help fulfill this two-fold mission, Diné College actively fosters a unique combination of traditional and Western learning. The College's educational philosophy, in all academic departments, is grounded in the Navajo traditional living system called Sá'ah

Naagháí Bik'eh Hózhóón, roughly interpreted as "walking or being in the pattern of beauty that surrounds you," or, in other words, placing human life in harmony with the natural world. Sá'ah Naagháí Bik'eh Hózhóón philosophy evolved from Hajiinai Bahané (ancient creation story) which explains the life, mistakes, and struggles of hardship, chaos, and harmony of Diyin Diné (Holy People). They corrected their own mistakes through prayers, songs, and ceremonies to heal themselves. The corrective measures taken by Diyin Diné became the basic teachings of Sá'ah Naagháí Bik'eh Hózhóón philosophy which consists of four inseparable parts:

- Nitsáhákees – consciousness or creative thought.
- Nahatá – planning, actions, and implementation of our thoughts and ideas.
- Iiná – living by achieving quality outcomes of thoughts and actions as a community.
- Siih Hasin – having the assurance of personal stability and satisfaction with life's achievements.

These key principles bring recognition and understanding of disturbances in the natural world caused by human misconduct and of ways to seek restoration. As such, all life forms, the natural world, and all of creation must be treated with utmost reverence and with understanding of natural order and properties. Therefore, within these ancient teachings the principles of Sá'ah Naagháí Bik'eh Hózhóón are relevant and applicable to modern environmental science, law, and policy issues.

Instruction at DEI, located at the Shiprock, New Mexico branch campus of Diné College, endeavors to unite the traditional Sá'ah Naagháí Bik'eh Hózhóón philosophy with Western environmental science methods. DEI environmental science teaching and research programs have been developed around the four Navajo sacred elements of natural systems – fire/light, air, water, and earth. DEI links objectives for curriculum, research, and community outreach to the four sacred elements as follows:

- Fire/Light – Assess different forms and increase the applications of *renewable energy* technology on the Navajo Nation, including solar and wind resources for families not connected to the grid, in a culturally sensitive manner.
- Air – Evaluate and improve both outdoor and indoor *air quality* affecting the health of Navajo people, including indoor radon and proper fuel use, and provide community education and outreach programs.
- Water – Evaluate and improve water quality including research and community outreach efforts with respect to groundwater quality, watershed management, erosion control, drought mitigation, rainwater catchment, and waterborne diseases.
- Earth – Conduct research and provide policy recommendations with respect to environmental health, sustainable and traditional agriculture, solid and hazardous waste management, reclamation of coal mines and abandoned mines, and soil and groundwater remediation, including natural and EA approaches.

Thus, this Navajo conception of and relationship to the environment – the natural elements of life – is strongly linked to the use of core ancient Navajo principles and values that guide environmental education and research. DEI students and interns are introduced and held to the principles and values that are framed and integrated with the process.

6.3.2 *Diné Environmental Institute as a Stakeholder*

DEI is currently expanding its role as the higher education center of the Navajo Nation for instruction, research, and community outreach addressing environmental and energy issues of importance to the Navajo people including sustainable land management, improvement of air and water quality, and development of clean energy, in addition to remediation of lands impacted by uranium mining and milling. DEI faculty and students administer and contribute directly to research and community outreach programs that are linked to classroom, field, and laboratory instruction. DEI faculty also have many years of experience addressing the environmental and energy issues of importance to the people of the Navajo Nation, including firsthand knowledge of the human health and environmental issues associated with the history of uranium mining and milling on Navajo land. Hence, in addition to its role as a contributor to the philosophy and science of remedies, DEI has emerged as a critical bridge among the larger group of stakeholders including federal regulators, research scientists, Navajo Nation agencies, and the Navajo people.

DEI's Uranium Education Program, in particular, plays a key role as an education and outreach umbrella for public health and environmental risks associated with the former uranium mining and milling industries on Navajo land. With comprehensive institutional knowledge of human health and environmental issues associated with uranium mining, milling, and remediation, coupled with lifelong practice of Navajo traditions and culture, DEI faculty have been instrumental in fostering stakeholder interaction and communication including DOE/Navajo agency meetings, Navajo Nation environmental conferences, and public gatherings. For example, at a DOE/Navajo Nation quarterly meeting, a DEI faculty member successfully argued the value of including a traditional healing ceremony for a Navajo resident employed as a DOE subcontractor at Monument Valley.

Although this chapter focuses on DOE's teaming with Diné College to help ask the right questions and then find answers for groundwater contamination at Monument Valley and Shiprock, many other stakeholders are involved. Table 6.1 presents an overview of all stakeholders and their roles in the remediation and long-term stewardship of uranium mill tailings sites on Navajo land administered under UMTRCA.

6.3.3 *Science of Natural and Enhanced Attenuation*

DOE and stakeholders involved in the remediation and long-term stewardship of uranium mill tailings sites on Navajo land are focused on natural and EA remedies in part because the approach compliments both Navajo tradition and Navajo Science.

Table 6.1 Stakeholders affected or involved in evaluating and mitigating human health and environmental risks from uranium mill tailings contamination on Navajo Nation land

Agency or group	Role and interests
General public	People interested in implementation of environmental laws, human health and environmental risks associated with uranium mill tailings, the design and long-term performance of remedies for uranium mill tailings contamination, and the science and implementation of natural attenuation remedies
Navajo people	Navajo people who share the interests of the general public and who are also concerned about the legacy of uranium mining and milling contamination on Navajo homelands, U.S. Government efforts to address this legacy, and the future environmental condition of legacy sites once remedies are in place
People in the vicinity of uranium mill sites and disposal sites	People who live near uranium mill sites on Navajo land, pump groundwater for domestic use and livestock, graze livestock and harvest game, and collect plants and soil for healing ceremonies, medicinal uses, and dyes
U.S. Environmental Protection Agency (EPA)	Federal agency responsible for developing standards, as authorized under the Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978, for mitigating health risks to the public, and for cleanup and long-term management of uranium mill tailings including standards for remedial action, groundwater quality, and long-term performance of tailings disposal cells; interested in the state of the science of enhanced natural attenuation strategies
U.S. Nuclear Regulatory Commission (NRC)	Federal agency responsible for enforcing U.S. EPA standards as authorized under the UMTRCA of 1978; also interested in the state of the science of enhanced natural attenuation strategies
Office of Legacy Management, U.S. Department of Energy	Federal agency responsible for compliance with U.S. EPA standards, as authorized under the UMTRCA of 1978 and as licensee to the U.S. NRC for long-term surveillance and maintenance of licensed Title I sites on Navajo land. Interested also, as a best management practice, in advancing the science of enhanced natural attenuation remedies
Navajo Abandoned Mine Land Reclamation Office, Navajo Nation	Navajo Nation agency responsible to the Navajo people for ensuring the remediation and long-term stewardship by the U.S. Government of all uranium mill tailings sites and disposal sites on Navajo land, and responsible for communicating to the Navajo people the current understanding of human health and environmental risks associated with these sites

(continued)

Table 6.1 (continued)

Agency or group	Role and interests
Diné Environmental Institute (DEI), Diné College	Community college institution of the Navajo Nation, responsible to the Navajo people for educating youth in the methods of Western environmental science in concert with Navajo traditions, language, and customs. As a research partner, DEI is an advocate of sustainable natural attenuation remedies. As an institution that blends science and culture, DEI has become a critical bridge between federal regulators, scientists, Navajo Nation agencies, and the Navajo people
Environmental Research Laboratory, University of Arizona	As a leader of environmental research and education in arid regions, the overall goal of the environmental research laboratory is to improve the health, welfare, and living standards of communities in desert areas through the application of appropriate and sustainable technologies, and more specifically, to advance the science of natural and enhanced attenuation in arid environments
Farmington Agricultural Science Center, New Mexico State University	Research and extension service campus near Shiprock, New Mexico with overall goals of advancing sustainable agriculture, landscaping, energy, and soil and groundwater remediation, specifically phytoremediation with native phreatophytes, in northwestern New Mexico and the Navajo Nation

The connection between enhanced natural attenuation science and Sá'ah Naagháí Bik'eh Hózhóón tradition became apparent in early meetings between DOE and DEI and helped shape subsequent research and student involvement.

Although natural attenuation has been accepted elsewhere by regulatory agencies for many years, EA has only recently been forwarded by the scientific community as a distinct strategy. Before and into the early 1990s, most large-scale attempts to clean up contaminated soil and groundwater focused on engineering strategies. Engineering approaches included excavating and hauling large volumes of soil to landfills, and drilling wells and pumping large volumes of water to the surface for treatment (NRC 2000). By the mid 1990s, studies and experience had revealed several shortcomings. Excavating and hauling contaminated soil can damage natural ecosystems and potentially expose workers or nearby residents. Also, many conventional pump-and-treat remedies for groundwater contamination had not achieved cleanup goals (NRC 2000). Overall, engineered remedies have not always been successful in restoring contaminated soil and groundwater.

As awareness of the limitations of engineering approaches grew, research began revealing more fully how naturally occurring processes in soils and groundwater can transform or prevent the migration of contaminants (NRC 2000). Reliance on natural attenuation has increased as a consequence. Natural attenuation is now considered a tool for supplementing or even replacing engineered treatment systems. In some cases, including sites with uranium mill tailings contamination, natural attenuation can be used to manage groundwater contamination remaining after engineering approaches have removed or isolated the source of contamination (DOE 1996). The term "monitored natural attenuation" (MNA), as an alternative to active engineering approaches "...refers to the reliance on natural attenuation processes to achieve site-specific remedial objectives within a time frame that is reasonable compared to that offered by other more active methods. The 'natural attenuation processes' that are at work in such a remediation approach include a variety of physical, chemical, or biological processes that, under favorable conditions, act without human intervention to reduce mass, toxicity, mobility, volume, or concentration of contaminants in soil or groundwater." (EPA 1999)

The natural physical, chemical, or biological processes most often referenced that can degrade or dissipate contaminants in soil and groundwater include aerobic and anaerobic biodegradation, dispersion, volatilization, and sorption (e.g., see Ford et al. 2008). Phytoremediation is another attenuation process that is often categorized separate from microbiological, physical, and chemical processes. Phytoremediation and microbial denitrification are the natural attenuation processes DOE, Diné College, University of Arizona, and New Mexico State University students and researchers are jointly investigating at Navajo uranium mill tailings processing and disposal sites.

Although the basic idea is quite old, the concept of using plants for natural attenuation didn't take root until the 1970s, and since then has been studied and applied primarily in wetland and humid upland settings. EPA defines phytoremediation as a set of technologies that use different types of plants for containment, destruction, or extraction of contaminants (EPA 2000). Some general categories of phytoremediation include degradation, the breakdown of contaminants in the root zone or through plant metabolism; extraction, the accumulation of contaminants in shoots and leaves and subsequent harvesting of the crop to remove the contaminant from the site; and immobilization, sequestration of contaminants in soil or hydraulic control of groundwater via evapotranspiration. A review of literature suggests that research using native, desert, phreatophytic shrubs for phytoremediation in the Monument Valley, Arizona and Shiprock, New Mexico deserts is new and innovative.

Microbial denitrification, as discussed here, is a technology that encourages growth and reproduction of indigenous microorganisms to enhance denitrification in both soil and the saturated zone. Denitrification ultimately produces molecular nitrogen (N_2) through a multistep process that results first in the intermediate gaseous nitric oxide (NO), then nitrous oxide (N_2O) (Tiedje 1994). Denitrification completes the cycle by returning molecular N_2 to the atmosphere. The process is performed primarily by heterotrophic bacteria and several species of bacteria that may be involved in the complete reduction of nitrate to nitrogen gas. Denitrification requires electron donors such as organic matter or another carbon source to reduce oxidized forms of nitrogen.

In 2003, DOE introduced the concept of EA and developed the technical basis and documentation to use EA as a transition between active engineered remedies and sustainable remedies that rely solely on natural processes (SRNL 2006). The EA concept is a departure from the classical definition of MNA (EPA 1999). An *enhancement* is any type of human intervention that might be implemented in a source-plume system that increases the magnitude of or accelerates attenuation by natural processes beyond what occurs without intervention. EA is a strategy that bridges the gap between active, engineered solutions, and passive MNA. A successful enhancement is also a sustainable manipulation – it does not require continuous, long-term intervention. Hence, EA requires a short-term, sustainable manipulation of a natural attenuation process leading to a reduction in mass flux of contaminants. In many cases, sustainable enhancements of natural processes are needed to achieve a favorable balance between the release of contaminants from a source (source loading) and attenuation processes that degrade or retard migration of contaminants in resultant plumes. For DOE and Diné College research purposes at Navajo UMTRCA sites, EA refers to sustainable interventions that enhance phytodegradation of nitrate, evapotranspiration for hydraulic control, and microbial denitrification.

6.4 Monument Valley, Arizona Pilot Studies

Students and faculty from Diné College and University of Arizona researchers are working with DOE on pilot studies of EA remedies for contaminated groundwater at a former uranium-ore processing site near Monument Valley, Arizona (Waugh et al. 2010). Nitrate and ammonium levels are elevated in an alluvial aquifer, and the contaminant plume is spreading away from a source area where a uranium mill tailings pile once stood. Pilot studies were designed to answer two questions: (1) what is the capacity of natural processes to remove nitrogen and slow plume dispersion, and (2) can we efficiently enhance natural attenuation if necessary? In other words, what is Mother Earth already doing to cleanse desert soil and groundwater, and how can we help her? Phytoremediation is also in harmony with the Navajo Nation's revegetation and range management goals for the site.

This section highlights several aspects of the Monument Valley pilot studies that have been supported by Diné College students and local residents, including site characterization, planting, monitoring, and data interpretation. Researchers and students developed the following objectives for the pilot studies:

1. Manage soil water balance and deep percolation, much like an evaporation cover for landfills, to control loading of nitrate and ammonia from the soil source into the alluvial aquifer.
2. Remove nitrate and ammonium from the soil source by enhancing natural phytoremediation and microbial denitrification.
3. Reduce nitrate and ammonia concentrations in the alluvial aquifer to less than 44 mg/L, the EPA standard, and slow the spread of the plume, again by enhancing natural phytoremediation and microbial denitrification.
4. Create a beneficial use of nitrate and ammonium by growing plants that produce seed for use in rangeland improvement plantings and mine land reclamation on the Navajo Nation.

5. Restore the ecology of land disturbed by the milling operation and by site remediation to native plant communities with the goal of improving management of land for both wildlife habitat and sustainable livestock grazing.

6.4.1 *Background Information*

The DOE Monument Valley Processing Site is located in Cane Valley in northeastern Arizona, 26 km south of Mexican Hat, Utah (Fig. 6.1). Uranium was first discovered in 1942 approximately 1 km west of the site by Luke Yazzie, a local resident. An estimated 696,000 metric tons of uranium and vanadium ore were mined from the deposit between 1943 and 1968. From 1955 until 1964, ore was processed by mechanical milling followed by chemical flocculation. The finer-grained material, higher in uranium content, was shipped to other mills such as the one at Shiprock, New Mexico, for chemical processing. Coarser-grained materials were stored on site.

From 1964 until 1968 an estimated 998,000 metric tons of tailings and low-grade ore were processed using batch and heap leaching. Uranium and vanadium were batch-leached by flowing sulfuric acid solution through sandy tailings placed in lined steel tanks. Heap leaching consisted of percolating a sulfuric acid solution through crushed, low-grade ore spread on polyethylene sheeting. Both operations used ammonia, ammonium nitrate, and quicklime (calcium oxide) to produce a bulk precipitate of concentrated uranium and vanadium. The tailings and processing solutions were discharged to a tailings pile and evaporation pond downslope from the processing area. The mill closed in 1968, and most of the mill buildings were removed shortly thereafter. Surface remediation of the site, from 1992 to 1994, included excavation and hauling of tailings and other site-related contamination to the Mexican Hat Disposal Cell. Analysis of soil within the footprint of the tailings piles at the time of tailings remediation indicated that residual ammonium and nitrate may be contributing to nitrogen contamination in the shallow, alluvial groundwater. Nitrate is the constituent of greatest concern in alluvial groundwater because concentrations exceeded the EPA groundwater standard of 44 mg/L for nitrate.

6.4.2 *Plume Source Containment and Removal*

Phytoremediation and enhanced microbial denitrification are the natural processes DOE and stakeholders are investigating to contain and remove the nitrate plume source. The evaluation of phytoremediation began with characterization of the ecology of the site in part to determine if native plant species could be used for phytoremediation.

Two native phreatophyte populations occur at the site: *Atriplex canescens* and *Sarcobatus vermiculatus* (díwózhii_beii and díwózhiishzhiin in Navajo, and fourwing saltbush and black greasewood in English). Phreatophytes at the Monument

Fig. 6.3 Diné College students Alverae Laughter and Westin Lee measuring fourwing saltbush plants as part of a greenhouse study of stunted growth and micronutrient supplements at the Tsaile, Arizona campus

Valley site may act, in essence, as passive, solar-powered, pump-and-treat systems for nitrate and ammonium in the source area and alluvial aquifer. *S. vermiculatus* is considered an obligate phreatophyte requiring a permanent groundwater supply and can transpire water from aquifers as deep as 18 m below the land surface (Nichols 1994). *A. canescens*, a facultative phreatophyte, takes advantage of groundwater when present but can tolerate periods of low water availability. The rooting depth of *A. canescens* may exceed 12 m (Foxx et al. 1984).

With assistance from local residents, about 1.7 ha of the source area for the nitrate plume, where tailings had been removed, was planted in 1999, mainly with the native desert shrub *A. canescens*. Another 1.6 ha of the source area was planted in 2006. The purposes of this phytoremediation cover were (1) to control the soil water balance through evapotranspiration, limiting deep percolation and contaminant seepage and (2) to extract and convert ammonium and nitrate into plant tissue. A rectangular irrigated plot was planted with approximately 4,000 *A. canescens* seedlings raised in a greenhouse at the University of Arizona. Navajo Department of Agriculture had confiscated the seed from an illegal harvesting operation on Navajo land. A drip irrigation system was installed to accelerate growth and enhance denitrification. In the future, replacement plants will be grown by students in a Diné College greenhouse near Tuba City, Arizona.

Growth of *A. canescens* transplants in portions of the 1999 planting remained stunted for several years. A greenhouse study conducted by Diné College students (Fig. 6.3) and faculty at the Tsaile, Arizona campus helped identify the cause of

Fig. 6.4 Diné College students Garry Jay and Rita White sampling soil for nitrogen content as part of soil and groundwater phytoremediation pilot studies at Monument Valley, Arizona

stunted growth. Results suggest that stunted growth occurs where iron and manganese coprecipitated as soft concretions during the milling process, possibly reducing the plant-availability of certain micronutrients. The greenhouse study suggested that micronutrient supplements could restore healthy growth rates (DOE 2007).

A. canescens shrub growth and nitrogen uptake have been monitored since 2000 using field sampling and QuickBird satellite images (DOE 2008). Plant canopy cover and growth rates have steady increased but varied across the plantings in response to the age of the planting, irrigation rates, and soil fertility. Annual nitrogen uptake, estimated from plant canopy volume, plant biomass, and nitrogen content on the basis of biomass, has been over 200 kg in mature plantings (DOE 2008).

Soil cores are collected annually with help from DEI students and local residents in the source area soils and analyzed for nitrate, ammonium, and sulfate (Fig. 6.4). Total soil nitrogen had been reduced from 350 to 200 mg/kg. These data show that planting and irrigating the source area has been exceptionally effective in removing nitrate from the soil. However, the data also show that nitrogen removal far exceeds what can be attributed to plant uptake. A salt-balance evaluation and a study of ^{15}N enrichment in the residual nitrate show that the nitrate loss can be attributed primarily to microbiological processes and not leaching (DOE 2009). A soil microcosm study and field observations support a hypothesis that nitrification occurs when source area soils are drier, and denitrification occurs at higher moisture contents (Jordan et al. 2008).

One objective of planting phreatophytes in the source area was to control the soil water balance and limit percolation and leaching of nitrate, much like an evapotranspiration disposal cell cover (Albright et al. 2010). Plantings were purposefully underirrigated to prevent recharge. Soil moisture profiles are monitored with help from local residents using neutron hydroprobes and time-domain reflectometry, and percolation flux is monitored with water fluxmeters (Gee et al. 2009) to evaluate the dynamic soil water balance. Results indicated yearly declines in water content at all depths, a likely response to increasing leaf area and transpiration, and zero percolation in all locations (DOE 2009). These results are evidence that the phytoremediation planting has cut off the plume from its source. Precipitation and irrigation are stored in the fine sand until seasonally removed by evapotranspiration and are not percolating and leaching nitrate.

6.4.3 *Enhanced Attenuation of the Plume*

DOE, Diné College, and University of Arizona researchers are also evaluating natural and EA remedies for groundwater contamination in the alluvial aquifer at Monument Valley, with a focus on two attenuation processes: phytoremediation to remove nitrate and ammonia and to slow plume dispersion, and microbial denitrification.

A. canescens and *S. vermiculatus*, if rooted into the nitrate plume, could be contributing to natural attenuation in two ways: (1) transpiration of water from the plume, slowing its dispersion from the site and (2) uptake of nitrate from the plume. Stable isotope methods, used to evaluate plant extraction of water and nitrate (DOE 2009), support the hypothesis that *S. vermiculatus* is an obligate phreatophyte rooted into the plume, whereas *A. canescens* is a facultative phreatophyte that uses both plume water and vadose zone water, and that both plant species are extracting nitrate from the plume.

Preliminary studies found that protecting existing stands of *A. canescens* and *S. vermiculatus* from grazing could double biomass production, transpiration rates (water extraction from the aquifer by plants), and nitrogen uptake rates (McKeon et al. 2006). These studies also demonstrated how, on a small scale, greenhouse-grown transplants of native shrubs could be established in denuded areas of the plume, and with managed irrigation, send roots 9 m and deeper into the alluvial aquifer. With managed grazing, phreatophytic shrubs growing over the nitrate plume could extract enough water to slow the spread of the plume during the time it takes for denitrification to reduce nitrate to safe levels. Transpiration rates of individual *A. canescens* and *S. vermiculatus* plants, measured both inside and outside grazing exclosure plots using sap-flow instrumentation, coupled with landscape-scale monitoring using QuickBird and Moderate Resolution Imaging Spectrometer (MODIS) satellite estimates of shrub cover (Glenn et al. 2008), suggest that an increase of 30 mm/year in annual evapotranspiration over the plume through enhanced vegetation abundance could tip the water balance of the aquifer from recharge to discharge.

Early pilot studies suggested that natural denitrification is occurring in the plume (McKeon et al. 2005, 2006). Nitrate levels in the alluvial aquifer decrease with distance from the source area and have also decreased over time. Part of the decrease is likely due to dilution, but part of the nitrate may have been lost to microbial denitrification. An investigation of natural process called ^{15}N enrichment in the plume suggested that up to 60% of a drop in nitrate from the source out to the leading edge of the plume can be attributed to denitrification.

Results of a feasibility study of enhancing natural groundwater denitrification processes (DOE 2008; Carroll et al. 2009) confirmed that the natural attenuation of nitrate is occurring at the site, and that although natural attenuation is occurring, it may take more than 150 years to achieve cleanup standards without enhancements. However, the feasibility study also suggested that the injection of ethanol as a substrate for denitrification could substantially increase groundwater denitrification rates and shorten the cleanup time by more than 100 years. A field-scale ethanol injection study is underway.

With assistance from local residents, University of Arizona developed an unobtrusive approach for evaluating changes in phreatophytic shrub populations based on remote sensing technologies at Monument Valley (Glenn et al. 2008). The research used a combination of field measurements and remote sensing to measure transpiration by *S. vermiculatus* and *A. canescens* growing over the nitrate plume at the site. Heat balance sap flow sensors were used to measure transpiration by the two phreatophytes, and results were scaled to larger landscape units and longer time scales using leaf area index (LAI), fractional vegetation cover, meteorological data, and the enhanced vegetation index from the MODIS sensors on the Terra satellite (Fig. 6.5). *S. vermiculatus* tended to have higher transpiration rates than *A. canescens*. The results support the premise that managing grazing could slow or halt the movement of the contamination plume by allowing the shrub community to extract more water than is recharged in the aquifer.

6.4.4 Summary: Article in the Gallup Independent, a Local Newspaper

In 2006, a journalist with the Diné Bureau of the Gallup Independent, after hearing about the research at Monument Valley, journeyed to the remote site to see for herself. The following quotes from her May 1, 2006 article in the Gallup Independent tell what she learned, show how she communicated the benefits of the Diné College collaboration to her Navajo readers (stakeholders), and provide a fitting summary of the Monument Valley project.

> "When people in this area think of plants, they may naturally think of dyes for weaving, or medicinal herbs, but they don't usually think of plants as remedies to remove contamination from places like uranium mills. However, that is exactly what some plants in the area are doing. There is currently a pilot study in Monument Valley involving plants and soil microbes that will help remove nitrate from groundwater."

Fig. 6.5 Cane Valley residents Mary and Ben Stanley sampling grazed black greasewood plants to determine leaf area index as part of a study of remote sensing methods for long-term, landscape-scale monitoring of phreatophyte transpiration

> "The project is a collaborative effort between Navajo Nation officials, scientists with the U.S. Department of Energy, University of Arizona researchers, and students from Diné College. The study is jointly funded by DOE and the University of Arizona. The DOE is also providing funds to Diné College so that interns can participate in the research."
>
> "The group strongly believes that caring for Mother Earth and restoring the health of the desert land are part of the Navajo way of life, and have implemented these same concepts into their project. A conventional cleanup strategy would be to drill wells and pump the groundwater to an aboveground treatment facility, but the group is looking into alternative remedies that would be more sustainable and would require less intervention."
>
> "Instead of a more Westernized cleanup method, the group began looking into more natural methods. They observed that two native plants in particular were withdrawing nitrate from both the soil source and the plume, and are actually converting nitrate into healthy plant tissue. Along with restoring and putting things back into balance, which is a primary concept in Navajo culture, the project is helping prevent deep seepage of nitrate into groundwater."

6.5 Shiprock, New Mexico Phytoremediation Pilot Studies

DEI students from the Shiprock, New Mexico campus, researchers from the New Mexico State University Agricultural Science Center south of Farmington, New Mexico, and researchers from the University of Arizona Environmental

Research Laboratory are collaborating with the DOE on phytoremediation pilot studies near the Shiprock UMTRCA Disposal Site. Groundwater in the vicinity of the site was contaminated with uranium, selenium, nitrate, sulfate, and associated constituents as a result of uranium milling operations in the 1950s and 1960s. The goal of phytoremediation in these areas is hydraulic control, to limit the spread of groundwater contaminants.

6.5.1 Shiprock Uranium Processing and Remedial Action

The Shiprock Disposal Site sits on a terrace above the San Juan River within the Navajo Nation town of Shiprock, about 28 miles west of Farmington, New Mexico (Fig. 6.1). The 93 ha (230 acres) of land occupied by the mill, ore storage area, tailings piles, and raffinate ponds (ponds that contain spent liquids from the milling process), were leased from the Navajo Nation starting in 1954 until the lease expired in 1973, when control of the land reverted to the Navajo Nation.

The Shiprock mill processed uranium–vanadium ore hauled primarily from mines located on Navajo land in the Carrizo Mountains, Lukachukai Mountains, and Sanostee Wash areas in northeastern Arizona and adjacent San Juan County, New Mexico. The Shiprock mill also processed uranium–vanadium products from the Monument Valley mill, uranium ore from the Lisbon Valley area in Utah and the Grants area of New Mexico, and, after the Durango, Colorado, mill was closed in 1963, uranium ore from mining districts in southwestern Colorado.

At the Shiprock mill, ore was crushed and then leached in a bath of sulfuric acid and oxidant to solubilize uranium and vanadium. Precipitation of uranium from the solution was accomplished by increasing the acidity and boiling to expel carbonate, followed by neutralization with magnesia.

When milling operations ceased in 1968, contaminated materials including the mill and other buildings, the raffinate pond area, and about 1.5 metric tons of mill tailings contained in two piles remained at the mill site above the San Juan River floodplain. After the facility reverted to Navajo Nation control in 1973, Navajo Engineering and Construction Authority (NECA) used the tailings as a training ground for heavy equipment operators. Between 1974 and 1978, NECA worked to consolidate and stabilize the tailings piles with guidance from the U.S. EPA.

In 1983, after passage of UMTRCA, the DOE entered an agreement with the Navajo Nation for cleanup, and afterwards, long-term care of the Shiprock mill site. Contaminated materials were consolidated in a disposal cell and covered. In 1996, NRC issued a general license to DOE for custody and long-term care of the disposal cell; however, contaminated groundwater remained in shallow alluvial material and in weathered and fractured shale bedrock beneath the former mill site. In 2003, DOE began pumping groundwater from the terrace and floodplain areas into an evaporation pond, but by 2004, pumping had produced only about half the expected amount. In 2004, DOE developed recommendations for improving the groundwater treatment system including an evaluation of phytoremediation, in this case the use of deep-rooted native plants to enhance evapotranspiration of terrace water and thus limit spread of the plumes.

6.5.2 Phytoremediation Pilot Study Objectives and Progress

In 2006, DOE, Diné College students and their collaborators from University of Arizona and New Mexico State University began to evaluate the feasibility of phytoremediation at the site. The concept was to use deep-rooted native plants to enhance evapotranspiration in an area south of the disposal cell where nitrate levels are elevated in alluvial sediments, and on a terrace between the disposal cell and an escarpment above the San Juan River floodplain to the north of the disposal cell where a uranium plume enters the floodplain. The goal of phytoremediation in these areas is hydraulic control, to limit the spread of contaminants in groundwater.

At Shiprock, Diné College students and faculty are helping to evaluate transplanting methods for native phreatophytes, plant water extraction rates, and contaminant uptake risks in phytoremediation test plots established overlying the nitrate plume and above the floodplain escarpment. Students participate in field activities and data analysis in the classroom.

The objectives of the pilot studies follow:

1. Establish native phreatophytes by transplanting seedlings started in a greenhouse and then irrigating transplants until roots have accessed plume groundwater.
2. Once plant roots have accessed groundwater, evaluate the human health and ecological risks associated with uptake of groundwater constituents and accumulation in aboveground plant tissue.
3. Evaluate the potential beneficial effects of phytoremediation on plume water volume, plume migration, and flow in existing contaminated seeps at the base of the escarpment and in floodplain groundwater.

Hydraulic control, in the context of phytoremediation, can be defined as the use of plants to transpire groundwater in order to contain or control the migration of contaminants (EPA 2000). An increase in water extraction rates may occur naturally over time as populations of phreatophytes establish above the nitrate plume and on the terrace above the San Juan River floodplain. However, if feasible, manipulation or enhancement of the plant ecology with the goal of accelerating water extraction by plants may be an economical addition to the current groundwater remedy.

Passive phytoremediation (no human intervention) and hydraulic control are already ongoing at Shiprock above the nitrate plume and on the river terrace. Volunteer plants of black greasewood (*Sarcobatus vermiculatus*), four-wing saltbush (*Atriplex canescens*), and rubber rabbitbrush (*Ericameria nauseosa*) currently growing above the nitrate plume are likely extracting water, nitrate, and possibly other groundwater constituents. A few scattered black greasewood plants that have "volunteered" on the terrace above the floodplain are likely removing water that

Fig. 6.6 Diné College students Thoer Peterman and Beverly Maxwell sampling soils for physical and chemical properties, and transplanting native phreatophytes to establish phytoremediation test plots at Shiprock, New Mexico

might otherwise surface in contaminated seeps at the base of the escarpment. Higher rates of water extraction by woody plants in both locations may improve hydraulic control.

Planting these areas – enhanced phytoremediation – may be an economical addition to the current groundwater compliance strategy. The success of enhanced phytoremediation would depend on several factors: depth to groundwater, phytotoxicity of groundwater constituents, site preparation methods, plant species selection, planting methods, soil amendments, and natural disturbances. The purpose of this pilot study is to begin evaluating the feasibility of phytoremediation at Shiprock.

Diné College students and collaborators set up two test plots in 2006 in a soil borrow pit overlying the nitrate plume, and two test plots in 2007 on the terrace between the disposal cell and the escarpment above the San Juan River floodplain. Students and faculty planted the four test plots using native *A. canescens* and *S. vermiculatus* transplants grown in greenhouses at the University of Arizona from seed acquired on Navajo land (Fig. 6.6). Students assembled the irrigation system with assistance from New Mexico State University. An employee of the Navajo Nation Abandoned Mine Lands Reclamation Department regularly filled the irrigation holding tanks with San Juan River water. Diné College students irrigated plants on a regular schedule and maintained the plantings, plot fences, and the irrigation system.

Students measured plant canopy dimensions in all plots in October 2007 and again in October 2008. Overall, plants in the terrace plots had grown considerably more than plants in the nitrate plume plots even though the terrace plots were planted a year later. At each location, differences in plant growth between plots were not significant. Values for the different growth parameters were more dispersed (greater variability) in 2008 than in 2007; some plants grew rapidly between 2007 and 2008 while others grew very little. The inconsistent growth patterns may be attributable to insufficient irrigation in 2008. At this stage of the study, soil type and depth to groundwater do not appear to have influenced canopy size. In 2008, based on canopy cover and canopy volume measurements, *A. canescens* appeared to be a better candidate than *S. vermiculatus* for phytoremediation at Shiprock.

Water isotope signatures can provide evidence of volunteer and translanted phreatophytes rooting into the shallow groundwater plumes and, therefore, the feasibility of enhancing phytoremediation and hydraulic control. Oxygen and hydrogen isotope signatures were determined for plants growing naturally overlying the nitrate plume and on the terrace above the San Juan River floodplain, and for water from groundwater monitoring wells in these locations. Salt cedar (*Tamarix ramosissima*) and *A. canescens* plants were sampled from the nitrate plume area, *S. vermiculatus* plants were sampled on the terrace above the escarpment, and *T. ramosissima* were sampled in the San Juan River floodplain.

Enrichment of water in heavy isotopes is expressed as δD and $\delta^{18}O$, in units of per mile (‰) compared to a seawater standard, with positive numbers representing enrichment and negative numbers representing depletion of heavy isotopes relative to the standard (Coplen et al. 2000). Water samples extracted from stem sections of plants generally have isotope signatures similar to the source of water tapped by plant roots. This makes it possible to infer the source of water used by a plant by comparing isotope signatures in the plant to those of potential sources of water in the environment accessible to the roots.

These principles were used to infer water sources of plants and well samples in this study. For this study, we used δD and $\delta^{18}O$ values reported for summer and winter rains at Page, Arizona, to plot the local meteoric water line (Lin et al. 1996). Diné College students and University of Arizona researchers sampled plant water and groundwater near the phytoremediation test plots in 2006 and again in 2007. Water isotope signatures for water in groundwater monitoring wells in the San Juan River floodplain, near the *T. ramosissima* plants sampled on the floodplain, were similar to river water, indicating that these wells are intercepting the floodplain aquifer recharged by the river. Water isotope signatures for the *T. ramosissima* plants sampled near the wells indicated that these plants are rooted into and using aquifer water for transpiration. An interpretation of water isotope signatures for volunteer *S. vermiculatus* plants growing on the escarpment suggests that these obligate phreatophytes are extracting plume water that rises by capillary action up into the escarpment. Water isotope signatures for *T. ramosissima* and *A. canescens* plants growing over the nitrate plume generally indicate that they are likely using locally recharged rainwater to support growth.

The primary purpose of the phytoremediation test plots located on the terrace at Shiprock is hydraulic control, to reduce the source of water for uranium-contaminated seeps at the base of the escarpment and for the uranium plume in the San Juan River floodplain below the escarpment. If plants are also accumulating toxic levels

Fig. 6.7 Diné College students (*left* to *right*: Stephanie Garcia with hood, unidentified student, Michelle John, Rita White, and Vanessa Todacheeny) sampling fourwing saltbush plants for analysis of heavy metal uptake in phytoremediation test plots at Shiprock, New Mexico

of uranium or other heavy metals in above-ground tissues, then the risks of bioaccumulation would be greater than the benefits of hydraulic control. Diné College students are assisting DOE to determine if native phreatophytic shrubs, both those that have naturally "volunteered" on the terrace and those planted to influence hydraulic gradients, are taking up uranium and other metals at levels high enough to be harmful. In 2009, students and DOE scientists designed and carried out a sampling plan to determine uranium and metal levels in stems, leaves, and seeds of planted and volunteer shrubs in and near test plots located on the terrace (Fig. 6.7). In 2010, students will apply standard statistical procedures to analyze data and evaluate human health and the environmental risks of uranium and heavy metal bioaccumulation.

6.5.3 Summary: National Science Foundation Documentary

Collaboration between DOE and the DEI of Diné College on phytoremediation research at the Shiprock Disposal Site received national recognition in the National Science Foundation documentary film, " Weaving STEM Education and Culture: The Faces, Places, and Projects of the Tribal Colleges and Universities Program." The documentary highlights high-quality STEM instructional and outreach programs within the National Science Foundation's Tribal Colleges and Universities Program (TCUP) (http://www.nsftcup.org/).

The following quotes, from interviews with Diné College instructors and students in the documentary, are a fitting summary of the Shiprock collaboration. The quotes tell a story of collaboration among scientists from different cultures, respect for tradition, the value of diversity in learning, and hope for a new generation.

> "When I went to school, we only learned about Western science. When I started working here at this school, we came to learn about science from the Navajo perspective. Our teaching is 'honor thy mother; honor thy father.' That's the Indian people's teaching. That means your mother, the one that gave birth to you, and all the way back to First Woman, and then back to Mother Earth—Mother Earth is your mother. So if you mistreat your mother, there will be consequences."

Jack C. Jackson, a 75-year old instructor at the Tsaile campus of Diné College, explaining the importance of linking Western environmental science education with Navajo cultural traditions. As a young man, Professor Jackson was part of a Navajo delegation that convinced the U.S Congress to appropriate funds to build Diné College.

> "A lot of students we have here at Diné College, the majority of them, have not really heard the stories based on the old traditional teachings, and how to relate the teachings to science. That's what I do. I like to teach what I call Navajo Science. I learned a lot of it from my elders. In the past, many of our students were going out to other universities to study off of the reservation. They don't realize that right here on the reservation, there are many things that need to be studied. Look at all of this area, this natural laboratory."

Arnold Clifford, Navajo botanist and part-time Diné College instructor at the Shiprock campus, explaining the importance of incorporating traditional teachings in science curriculum and the need for continued research on the Navajo reservation.

> "What we're doing with the students at Diné College is a phytoremediation research project: phyto meaning 'plants', and remediation meaning 'a remedy to fix a problem.' So plants are being used to control the hydrology so the groundwater plume doesn't flow down into the San Juan River floodplain."

> "The Department of Energy is very interested in having students involved, to be aware of the risks and what the Department of Energy is doing to alleviate the risks in the long term. This is their land; they are the prime stakeholders. I think it's important for people who live here to understand and help come up with the remedies themselves. Fortunately, Diné College provides that opportunity."

Dr. Jody Waugh, an Environmental Scientist with a DOE contractor, Project Lead for phytoremediation research at Shirock, and part-time instructor at Diné College, explaining the need for DOE to collaborate with Diné College.

> "I think it's very important, especially from my own Tribe, getting involved and becoming a scientist, and being able to make an impact in our future."

Vanessa Todacheeny, Diné College student working on the phytoremediation research project at Shiprock.

> "I know that as a student, you can make changes. In the past, we couldn't speak out, but now we can become educated and learn more about things through research. Our ancestors, our elders, they tell you to respect Mother Nature, that you're not supposed to put it out of balance. Well, there is a way to put things back in balance, and you, as a student, have to find out that way. I want to someday be that student."

Rita White, Diné College student working on the phytoremediation research project at Shiprock.

6.6 Summary and Conclusions

DEI has become a key stakeholder and partner with the U.S. DOE in efforts to develop and implement sustainable and culturally acceptable remedies for soil and groundwater contamination at uranium mill tailings processing and disposal sites on Navajo Nation land. DEI is a center for environmental education, research, and community outreach located on the Shiprock, New Mexico campus of Diné College, the Navajo Nation institution of higher education. As a stakeholder, DEI plays a key role in shaping the philosophy of remedial actions, advancing the science of sustainable remedies, bridging communication and interaction among other stakeholders, listening to and responding to the concerns of the Navajo people, and training a new generation of scientists to address the uranium mining legacy and other environmental and energy issues on the Navajo homeland.

Through an educational philosophy grounded in the Navajo traditional living system called Sá'ah Naagháí Bik'eh Hózhóón, which places human life in harmony with the natural world, DEI has helped guide researchers to look beyond traditional engineering approaches and seek more sustainable remedies for contaminated soil and groundwater at former uranium mill sites near Monument Valley, Arizona, and Shiprock, New Mexico. Following this philosophy, researchers are asking first, what is Mother Earth already doing to heal a land injured by uranium mill tailings, and second, what can we do to help her? This has led researchers to investigate applications of first, natural, and then, EA remedies involving native plants – phytoremediation, and indigenous microorganisms – bioremediation. Although such applications are fairly common in wetland and humid environments, EA in the desert is new and innovative.

DEI faculty and students are working side by side with university and DOE scientists on pilot studies aimed at developing sustainable remedies for contaminated soil and groundwater at Monument Valley and Shiprock. Diné College faculty, student interns, and local residents have contributed to several aspects of the pilot studies including site characterization, sampling designs, installation and maintenance of plantings and irrigation systems, monitoring, and data interpretation. Research results look promising.

At Monument valley, DOE removed radioactive tailings from the site in 1994. Nitrate and ammonium, waste products of the milling process, remain in an alluvial groundwater plume spreading from the soil source where tailings were removed. Planting and irrigating two native phreatophytic shrubs, fourwing saltbush and black greasewood, has markedly reduced both nitrate and ammonium in the source area over an 8-year period. Most of the reduction is attributable to irrigation-enhanced microbial denitrification rather than plant uptake. However, soil moisture and percolation flux monitoring show that the plantings control the soil water balance in the source area, preventing additional leaching of nitrogen compounds. Enhanced denitrification and phytoremediation also look promising for plume remediation. Microcosm experiments, nitrogen isotopic fractionation analysis, and solute transport modeling results suggest that most of the plume nitrate has been lost through natural denitrification since the mill was closed in 1968. Injection of ethanol may accelerate microbial denitrification in plume hot spots. Finally, landscape-scale remote sensing methods developed for the project suggest that transpiration from restored native phreatophyte populations rooted in the aquifer could limit further expansion of the plume.

At Shiprock, DOE contained mill tailings in an engineered disposal cell in 1986. Groundwater is contaminated by uranium, nitrate, and other constituents as a result of milling operations. Passive phytoremediation and hydraulic control are ongoing at Shiprock. Native phreatophytes are extracting water and possibly other groundwater constituents. Phytoremediation test plots were set up in 2006 with assistance from DEI students and faculty to evaluate the feasibility of enhancing hydraulic control. Researchers are evaluating several factors that will influence the success of enhanced phytoremediation including site preparation methods, establishment and growth of different plant species, root access of plume groundwater, and uptake and toxicity of groundwater constituents.

DEI's insight and experience implementing an educational policy that fosters diversity of thought, the joining of tradition and science, and the importance of community has been instrumental in building stakeholder relations. With firsthand knowledge of human health and environmental issues associated with the Navajo uranium legacy, lifelong practice of Navajo way of life, and experience directing community outreach programs, DEI faculty have been influential in helping mediate communication and interaction among stakeholders including federal regulators and administrators, research scientists, Navajo Nation agencies, and the Navajo people.

Finally, DEI and Diné College are training a new generation of scientists and community leaders who will write the next chapter in the Navajo story about uranium mining, milling, and environmental stewardship. They will know the history, they will continue the traditions, they will advance the science, they will facilitate the needed partnerships, they will inform the people, they will protect human health, and they will fulfill their duty as caretakers of Mother Earth, helping her restore and sustain the health of the land.

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