Chapter 6
The Mountain Regions of the United Arab Emirates: An Ecosystem Perspective

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6.1 The Mountain Regions as an Ecosystem

6.1.1 Physical and Structural Parameters: A Mountain "Reef" in a "Sea" of Sand

The mountain regions of the United Arab Emirates (UAE) are introduced in Chap. 2 (Fig. 6.1). They are part of the chain of mountains stretching for more than 600 km along the Gulf of Oman coast of Arabia, from the Musandam peninsula almost to Ras Al Hadd at the easternmost tip. Peaks and ridges in most of the UAE are generally 900 m or less in height, but in the Ru′us Al Jibal (the mountains of the Musandam) a few UAE summits exceed 1500 m and UAE territory in the broad summit area of Jebel Jais (pronounced *Yais*) reaches almost 1900 m.

The UAE's mountain regions receive mean annual rainfall of ca. 160–190 mm (UAE University 1993; Feulner 2011) and are therefore routinely classified as arid overall, although not hyper-arid (see also Chap. 3). The amount of annual precipitation, however, is only a crude measure of the nature of the environment. From an ecosystem point of view, the mountain regions of the UAE can more usefully be understood by analogy to a coral reef in the ocean environment, but in this case the mountainous "reef" is bounded by a "sea" of sand.

Like a coral reef, the extreme physical and structural diversity of the mountain landscape creates a wealth of habitats and microhabitats, differentiated by substrate, elevation, geochemistry, humidity, wind, aspect, exposure, shelter, vegetation cover, the timing of precipitation in relation to vegetative stages, the ability of the substrate to retain moisture, and more. These individualized parameters can ameliorate the effects of overall aridity, and exploitation of the many alternative habitats by different organisms results in substantial floral and faunal diversity (Fig. 6.2).

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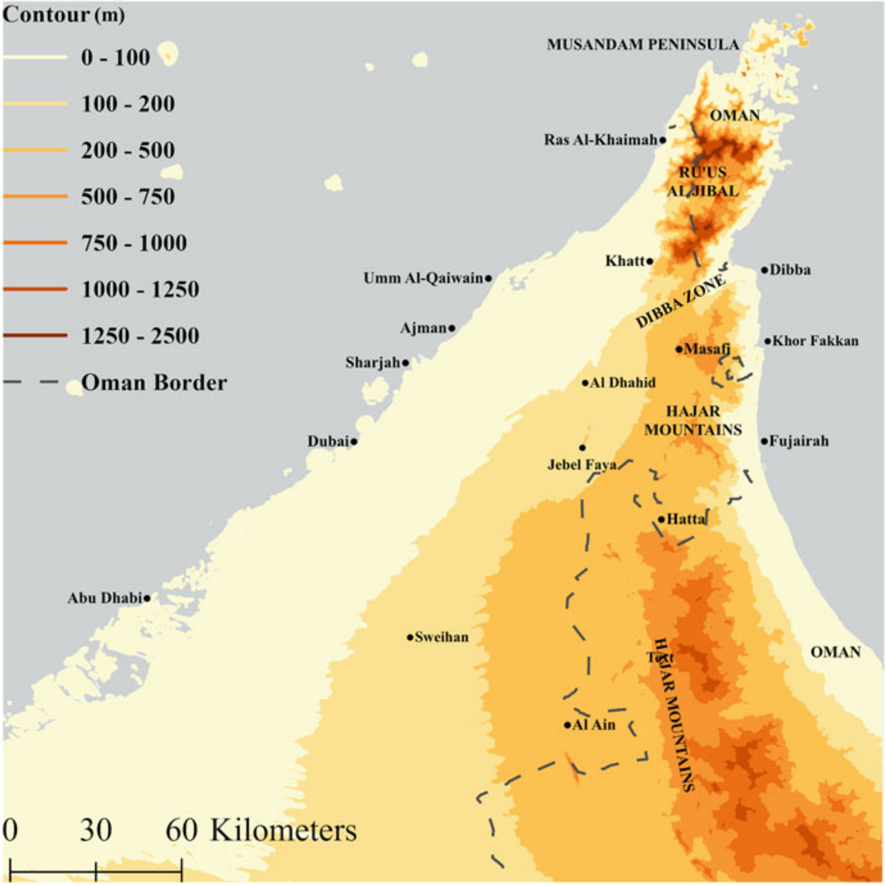

Fig. 6.1 A simplified geological map of the mountain areas of the UAE and northernmost Oman

Although the UAE's mountain regions occupy less than 5% of its surface area, it has routinely been estimated that they are home to more than 50% of its native plants and a comparable number of its animals, many of which are found only in the mountains. The final report of the September 2019 UAE Plant Red List workshop, conducted under the joint auspices of the UAE Ministry of Climate Change and Environment (MoCCE) and the International Union for the Conservation of Nature (IUCN), recognizes a total of 598 native plant species (Allen et al. 2021). Mountain plants are not separately identified in the final report, but somewhat more than 350 of the total (> 60%) are species found primarily or exclusively in mountain habitats.

The taxonomic nomenclature used for UAE flora in this chapter follows the lead of Chaps. 5 and 13 by adhering to the nomenclature used in Jongbloed et al. (2003), in order to allow non-specialist readers the opportunity to check plants in that widely-used book, available online. Exceptions are expressly noted in the text. In fact, although there have been considerable nomenclatural changes to the UAE flora as a whole over the intervening years, very few of the species mentioned in the text have been affected. Reference is made, however, to a small number of species not

Fig. 6.2 Wadi Mayy, Fujairah, after a "wet" winter season. Mountain areas of the UAE are home to some 60% of its native plants and probably a similar proportion of its animals. The number of plants and animals one can expect to see in a day is much greater in the mountain regions than in the sand deserts. Photo credit: Gary Feulner

included in Jongbloed et al. (2003) but only in subsequent works, particularly Feulner (2011).

6.1.2 Contributors to Biodiversity: Biogeographical Position, Endemism, Climate History

The UAE's privileged position at the junction of the three main Old World biogeographical regions (the Afrotropical, Palearctic and Oriental), and within the Eremic Zone (Larsen 1984) that today overlies that junction, makes an independent contribution to the biodiversity of the country (Fig. 6.3). The presence of Palearctic and Oriental floral and faunal elements is greatest in the mountain areas (Feulner et al. 2021). In terms more familiar to botanists, the mountain areas of the UAE are a meeting point for floral elements from the Saharo-Arabian, Nubo-Sindhian, Irano-Turanian and Mediterranean regions (Feulner 2011).

At the same time, the mountains of Eastern Arabia are sufficiently isolated from the mountains of Western Arabia, Dhofar and the Zagros that they have become an independent center of endemism. This has been recognized botanically (Ghazanfar 1999) but is best demonstrated by the reptile fauna. The UAE and Oman were long recognized to host two endemic lizard species (*Omanosaura cyanura* and *O. jayakari*), but early in the new millenium, a viper (Babocsay 2004), an agamid

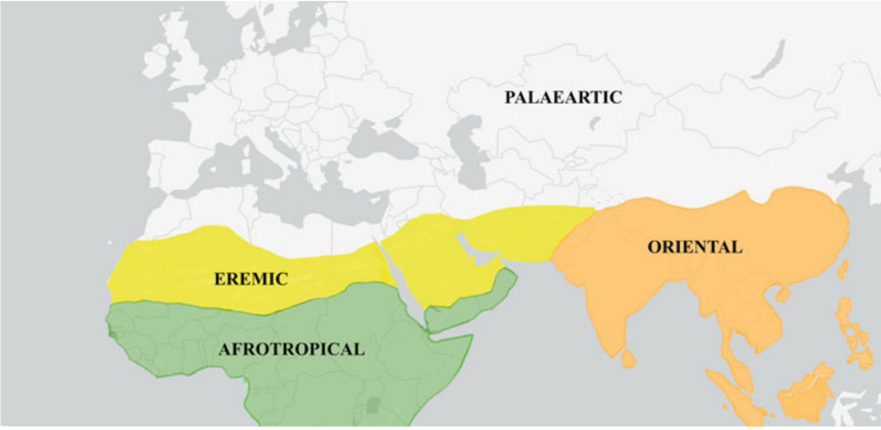

Fig. 6.3 The principal biogeographical regions of the Old World. Modified from Feulner et al. (2021) and reused with permission

(Melnikov et al. 2013) and a gecko (Nazarov et al. 2013) from the UAE/Oman mountains were segregated taxonomically from congeners (sister species) in Western Arabia and the Levant with whom they had previously been identified. More recently, "new" nocturnal geckos have been distinguished from cryptic counterparts within the UAE and Oman (Carranza et al. 2016; Simó-Riudalbas et al. 2017; Carranza et al. 2021). These newly defined species include two geckos limited to the mountains of the Musandam peninsula and a very restricted range gecko that has thereby become the UAE's only endemic vertebrate. The broader result is that 19 of the 28 reptile species that live in the mountains of the UAE and northern Oman are now considered endemic (Burriel-Carranza et al. 2022). Segregation of additional cryptic species among the UAE's diurnal geckos is anticipated from current work (Garcia-Porta et al. 2017, Burriel-Carranza et al. 2022). All this is discussed in more detail in Chap. 16.

The UAE is also home to at least one land snail endemic to the highest elevations in the UAE/Oman mountains (Feulner and Green 2003), a damselfly endemic to the dry wadis of the mountain interior (Feulner et al. 2007), and at least six of the larger but still somewhat speculative number of plant species endemic to the UAE/Oman mountains (Feulner 2016) (Fig. 6.4).

The mammalian fauna of the mountains is now dominated by feral goats. The native mammalian fauna is limited but includes a number of characteristic species such as Blanford's Fox *Vulpes cana*, Caracal *Caracal caracal schmitzi*, Brandt's Hedgehog *Paraechinus hypomelas*, Wagner's Gerbil *Gerbillus dasyurus*, Arabian Spiny Mouse *Acomys dimidiatus*, all relatively common, as well as the endemic Arabian Tahr *Arabitragus jayakari*, now threatened, and the Arabian Leopard *Panthera pardus nimr*, considered extinct in the UAE and northern Oman since early in the current millennium. See also Chap. 14.

Resident bird species include Chukar Partridge *Alectoris chukar* (effectively limited to the Ru′us Al Jibal), Sand Partridge *Ammoperdix heyi*, Rock Dove

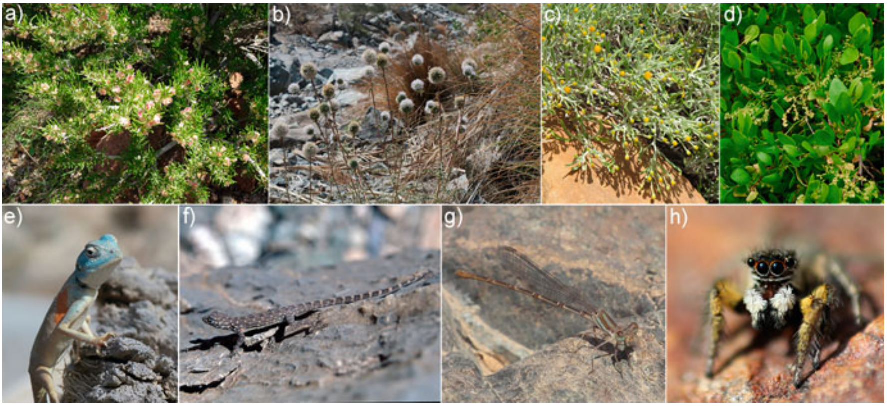

Fig. 6.4 Some UAE plants and animals endemic to the mountains of the UAE and northern Oman: (**a**) *Pteropyrum scoparium* (Polygonaceae), a woody shrub most common in harzburgite terrane; (**b**) *Echinops erinaceus* (Asteraceae), particularly common among scree accumulations; (**c**) *Pulicaria edmondsonii* (Asteraceae), common at medium elevations in both the Hajar Mountains and the Ru′us Al Jibal; (**d**) *Rumex limoniastrum* (Polygonaceae), very rare in both the UAE and Oman; (**e**) Hajar Rock Agama *Pseudotrapelus jensvindumi*, common, but only recently segregated from congeners in Dhofar and Western Arabia; (**f**) Bar-Tailed Semaphore Gecko *Pristurus celerrimus*. A primitive member of its genus, its tail signaling is less well developed than that of the *Pristurus rupestris* group (Feulner 2004); (**g**) Hajar Wadi Damselfly *Arabineura khalidi* (a female is shown here), widespread but easily overlooked; and (**h**) *Rafalus arabicus*, a common jumping spider, active on rocks even during the heat of the day (a male is shown here). Photo credits: Gary Feulner (a–g); Binish Roobas (h)

Columba livia, Laughing Dove (Palm Dove) *Spilopelia senegalensis*, White-Spectacled Bulbul *Pycnonotus xanthopygos*, Pale Crag Martin *Ptyonoprogne* (*fuligula*) *obsoleta*, Desert Lark *Ammomanes deserti*, Hume's Wheatear *Oenanthe albonigra*, Purple Sunbird *Cinnyris asiaticus*, Scrub Warbler *Scotocerca inquieta*, Long-Billed Pipit *Anthus similis*, Striolated Bunting *Emberiza striolata*, and several owl species. See also Chap. 15.

The temporal or historical dimension is another essential element for an understanding of the biodiversity and biogeography of the UAE. Together, the UAE's biogeographical position, its geographical position astride the Tropic of Cancer, mountain endemism, and the climatic oscillations of at least the past 500,000 years (Glennie 1991, 1996, 2001; Sanlaville 1992, 1998; Goodall 1994; Parton et al. 2015) and continuing into the Holocene (Parker 2009; Parker et al. 2004, 2016), have created a complex pattern of residual or relict populations, which survive in Arabia in refugia in the mountain regions. These include Palearctic species like the Wild Olive (*Olea europaea*), a native of Asia Minor and the Eastern Mediterranean; the White Edged Rock Brown (*Hipparchia parisatis*) and Loew's Blue (*Agrodiaetus loewi*) butterflies, native to Eurasian mountains (Larsen 1983, 1984; Feulner et al. 2021); and the Arabian Grizzled Skipper butterfly (*Spialia mangana*), whose recently discovered UAE and Oman populations are isolated outliers of a species today centered on Somalia (Feulner 2007; Feulner and Roobas 2014; Feulner et al. 2021) (Fig. 6.5).

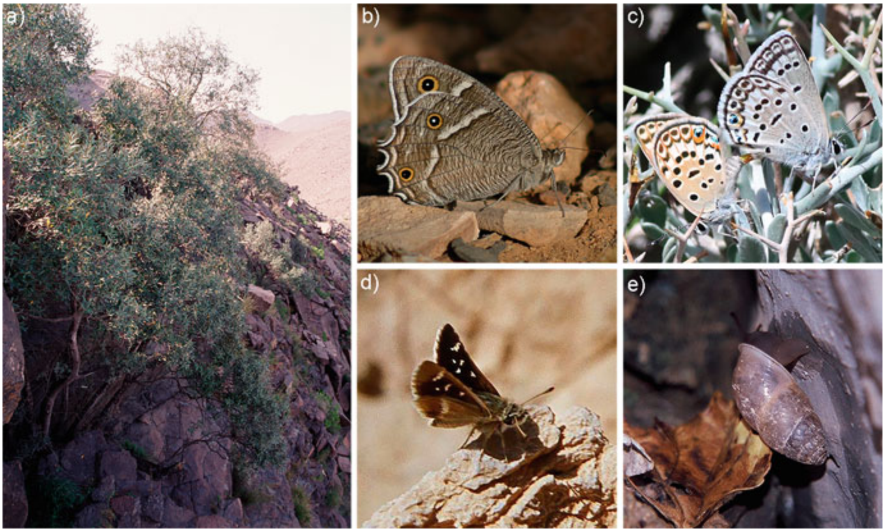

Fig. 6.5 Some UAE mountain plants and animals that are relict species, i.e., they were once more widespread at a time of more favorable climate, but have withdrawn to discrete pockets of congenial habitat in mountain areas: (**a**) Wild Olive *Olea europea*, shown here in the Olive Highlands southwest of Fujairah city. Wild Olives also occupy uninviting habitats in upper ravines along the spine of the Western Hajar from the Hatta area to the Jebel Akhdar, places where few botanists have ventured; (**b**) White Edged Rock Brown butterfly *Hipparchia parisatis*, a large Palearctic mountain species that still keeps its Palearctic schedule, even in the UAE (see text); (**c**) Loew's Blue butterfly *Agrodiaetus loewi*, a Palearctic species that is restricted in the UAE and Oman to intermediate elevations in the Ru′us Al Jibal, where its exclusive larval foodplant occurs, *Astragalus fasciculifolius* (Fabaceae); (**d**) Arabian Grizzled Skipper *Spialia mangana*. An isolated population of this sedentary butterfly was discovered in the Olive Highlands in 2013, in association with its presumed larval foodplant, *Melhania muricata* (Sterculiaceae) (see Fig. 6.19c); (**e**) *Mordania omanensis*, a 2 cm land snail endemic to the UAE and Oman mountains but found today only among bedrock cliffs at high elevation in the Ru′us Al Jibal and the Jebel Akhdar of Oman (Neubert 1998; Feulner and Green 2003). Photo credits: Gary Feulner (a,d,e); Oscar Campbell (b); Binish Roobas (c)

6.1.3 *Constraints Common to all UAE Mountain Ecosystems: Unpredictable Rainfall, Poor Soil and Overgrazing*

A number of distinctive sub-units of the UAE's mountain ecosystem are identified and briefly discussed below, but at the outset it is worth highlighting three limiting phenomena that are common to all of the mountain areas of the UAE, set against the general background of aridity.

The first is the unpredictability of rainfall. Most rain falls in the mountains between December and April and very little falls during summer and early autumn (Feulner 2006), although mountain front areas may experience scattered summer thunderstorms, especially southwards towards Al Ain. But while UAE rainfall patterns can be characterized statistically, that is not the same as seasonality. So it is important to emphasize that the UAE's statistical rainfall patterns are *not* highly reliable in terms of timing, and even less so in terms of amount. Rainfall in wet years can be more than five times the total in dry years (Feulner 2011) and much of the total annual precipitation can sometimes fall in one or a few rainfall events. And, despite occasional very "wet" years, e.g. the mid-1990s (1995–1998), long-term mean annual rainfall in mountain areas has been as described in Sect. 6.1.1 above (ca. 160–190 mm), so the "wet" years have ultimately been balanced by drought years, e.g. mid-1999 to mid-2003 (Feulner 2006). Rainfall variation for the UAE as a whole has been recognized to be periodic (Jongbloed et al. 2003; Feulner 2006) and appears to be related to the multi-year El Niño phenomenon (Emirates Wildlife Society-WWF 2006; Tourenq et al. 2011). The significance from an ecosystem perspective is that the terrestrial flora and fauna must be prepared to accommodate themselves to these relatively demanding conditions, and to survive the lean years.

The combination of extreme summer temperatures, low annual rainfall, and the unpredictability of rainfall pose challenges for the native flora and fauna of the UAE. Those same factors may, however, help to explain why, although developed and agricultural areas of the modern UAE are today home to countless species of exotic plants and animals, both invited and uninvited, very few of those introduced species have made significant inroads or had significant impacts in natural areas of the mainland UAE.

A second limitation is that soil is seldom developed to any significant extent, except in isolated pockets, or where specifically engineered for agriculture (Fig. 6.6), or (in recent decades) where floodwaters have deposited silt behind dams, in environments exposed to intermittent catastrophic events (see Sect. 6.3.2 Temporal Gradients, below).

Third, essentially all mountain areas of the UAE are heavily impacted by overgrazing, which has increased with growing affluence and has not been effectively controlled by legislation or cultural practices. The principal effects of overgrazing are the reduction of vegetative cover overall, the elimination of palatable herbs and shrubs, and the prevention of regeneration by large trees species. Thus the mix of species that we see in the UAE's mountains today may not closely resemble what was present even just two or three generations ago. The main culprits are feral and domestic goats, which can negotiate all but the most difficult terrain (Fig. 6.7). Camels are increasingly present in mountain wadis that are accessible by vehicle. Feral donkeys are also present in the mountains, but their numbers are small and they are generally limited to family groups of two to four animals, except on the fringes of human settlement. In wild areas they favor wadis, terraces and plains but they can also be found on slopes, except the treacherous middle and upper slopes of harzburgite areas. In popular discourse, donkeys seem to receive a disproportionate share of the blame for overgrazing, perhaps because they no longer have a human constituency with a vested economic interest in defending them. It can be argued that the population of feral grazers is at or near carrying capacity, since die-offs can be seen in times of severe drought, e.g., the turn-of-the-century drought from mid-1999 to mid-2003 (see Feulner 2006).

Fig. 6.6 A locally rare, edible fern *Ophioglossum polyphyllum* (**a**), usually associated with traditional agriculture, was discovered not far above the Wadi Wurayah waterfall, in (**b**) silty soil on a terrace that still shows the remains of a series of small cultivated plots along it. The downstream direction is towards the observer. Photo credits: Gary Feulner

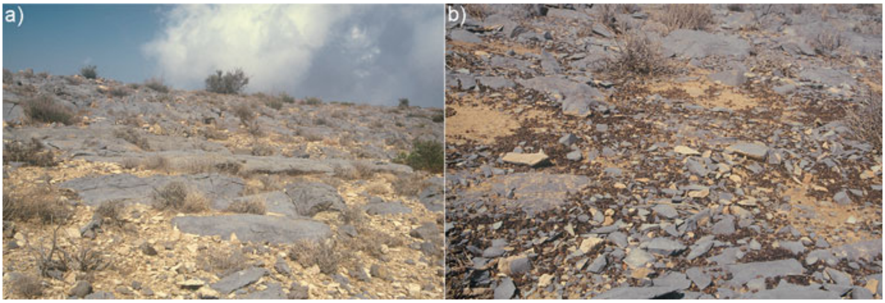

Fig. 6.7 Overgrazing in the mountain environment: (**a**) The barren summit of Ras Mintera (1800+ m), the third highest in the Ru′us Al Jibal, just a few kilometers north of Jebel Harim and far from any settlement. (**b**) A close-up reveals thousands of goat droppings that help to explain the state of the vegetation. Photo credits: Gary Feulner

6.2 The Principal UAE Mountain Ecosystems

Chapter 2 introduced the main geographical divisions of the UAE Mountains:

(a) the Hajar Mountains, comprising almost all of the mountain areas of the UAE to the south of the Musandam peninsula.
(b) the Ru′us Al Jibal in the north, occupying the Musandam peninsula.
(c) the Dibba Zone, which separates the Ru′us Al Jibal and the Hajar Mountains.
(d) the Foreland Ridges, a broken line of rocky hills and ridges west of the main mountain front, e.g., Jebel Hafeet near Al Ain and Jebel Faya and others, south of Dhaid.
(e) the Alluvial Plains which flank the mountains to the east and west, representing the product of erosion of the mountains over time.

These geographical units and a number of their specialized geological and ecological sub-units are discussed below from an ecosystem perspective.

6.2.1 The Hajar Mountains

The Hajar Mountains account for about 85% of the mountain areas of the UAE. They consist mostly of the brown-weathering igneous rocks of the UAE/Oman ophiolite, originally a thick slab of oceanic crust and uppermost mantle. Their topography is generally rugged and steep, but low foothills along the west flank can be deeply weathered. Exposed bedrock slopes are typically barren, with vegetation concentrated in wadis, wadi banks, terraces, slope rubble, lower slopes and gullies, especially of higher order tributaries. Main channels often appear to be swept clean of vegetation by occasional floods, but smaller tributaries can be relatively rich in life.

6.2.1.1 Hajar Mountain Wadis: Some General Considerations

Although vegetation cover is often conspicuously low in major wadi beds, they are nevertheless host to a large number of species overall (Brown and Sakkir 2004). The typical substrate of lower mountain wadis includes a substantial size range of coarse rocks and pebbles, with gravels and sands also locally present. The combination of different types of substrate, pronounced spatial heterogeneity in microtopography and microclimate, light availability, and regular access to water creates a patchwork of favorable microhabitats, making these environments floristically extremely rich overall.

Wadi beds are also highly dynamic habitats, not only in terms of their physical characteristics, but in terms of their floristic composition as well. This is primarily due to occasional rainfall events causing temporary inundation and rarer ‘catastrophic’ events causing severe flooding (Fig. 6.8). Many species can be decimated during torrents, but at the same time, new seeds are transported with the water and deposited in favourable microhabitats (Brown and Sakkir 2004).

It is certainly true that the same wadi can present very different appearances, both physically and floristically, depending on the recent history of rainfall and flooding, and on the season when the wadi is visited. Even some of the most abundant, colourful and conspicuous annual species, such as the mountain dock *Rumex vesicarius* (Polygonaceae) (Fig. 6.9h), may be all but undetectable during much of the year. In dry years many annuals may be absent altogether and many perennial species may be largely dormant.

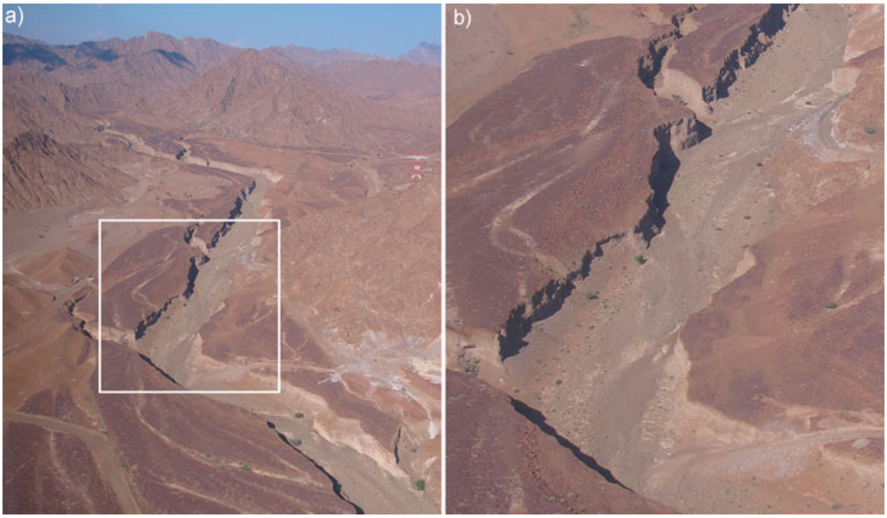

Fig. 6.8 In its lower reaches, the main northerly tributary of Wadi Wurayah (**a**) is broad and straight with a bed of coarse boulders, but closer inspection (**b**, inset) shows that small trees and shrubs nevertheless colonize the sloping wadi banks. Note that the present day wadi is carved into the center of a much broader historical valley filled with 10 m or more of coarse gravel, evidencing one or more earlier eras of more intense erosion. Photo credits: Gary Feulner

Fig. 6.9 Some common and widespread plant species of the Hajar Mountains of the UAE: (**a**) Mountain Spurge *Euphorbia larica* (Euphorbiaceae), one of the first shrubs to be refreshed after rain. (**b**) *Tephrosia apollinea* (Fabaceae), untouched by quadrupeds. (**c**) *Leucas inflata* (Lamiaceae), recognizable by its regular geometry. (**d**) *Aizoon canariense* (Aizoaceae), widespread throughout the Eremic zone, but uncommon in the Ru′us Al Jibal. (**e**) Prostrate, spiny *Fagonia bruguieri* (Zygophyllaceae). (**f**) *Tribulus terrestris* (Zygophyllaceae), a widespread Afro-Asian species. (**g**) Wadi Fig *Ficus salicifolia* (Moraceae). (**h**) Mountain Dock *Rumex vesicarius* (Polygonaceae). (**i**) *Ochradenus aucheri* (Resedaeae), with leafless, whip-like stems. (**j**) Sidr tree *Ziziphus spina-christi* (Rhamnaceae), a magnificent specimen along the middle reaches of Wadi Wurayah. Photo credits: Gary Feulner

6.2.1.2 Floral Elements Common to Hajar Mountain Habitats Generally

A number of plant species are common throughout the Hajar Mountains (and the mountains of the UAE generally) and occur in all or most of the ecological sub-units discussed here. These include Mountain Spurge *Euphorbia larica* (Euphorbiaceae), Umbrella Thorn *Acacia tortilis* (Fabaceae) and the geometric mint *Leucas inflata* (Lamiaceae) on slopes; the unpalatable legume *Tephrosia apollinea* (Fabaceae), which often predominates on wadi banks and in gullies at low and medium elevations; the prostrates *Aizoon canariense* (Aizoaceae), *Fagonia bruguieri* (Zygophyllaceae) and *Tribulus terrestris* (Zygophyllaceae) on terraces; and the Wadi Fig *Ficus salicifolia* (Moraceae), Mountain Dock *Rumex vesicarius* (Polygonaceae), the whip-like *Ochradenus aucheri* (Resedaceae) and the Sidr tree *Ziziphus spina-christi* (Rhamnaceae) along wadis (Fig. 6.9).

The foundational introductory account by Western (1989) accurately characterized the flora of the UAE mountains as a whole, except at the highest elevations, as a *Euphorbia larica—Tephrosia apollinea* association.

Most of the foregoing species are also regionally widespread. Nevertheless, even these common and widespread species are not uniformly distributed. Field work in the mountains of the UAE is arduous and quantitative comparison studies are non-existent, but wide-ranging qualitative investigations over many years confirm the expected result, that the mix of plant species present varies significantly among the different ecological units discussed here, most of which are based on geology (see, e.g., Feulner 1997, 1999b, 2011, 2014, 2016; Jongbloed et al. 2003; El-Keblawy 2011; El-Keblawy et al. 2016).

The following sections briefly introduce the most important ecological sub-units of the Hajar Mountains.

6.2.1.3 Harzburgite Terrane

"Terrane" is a geological term that denotes an extensive and more or less contiguous body or area of rock(s) of similar kind, origin and/or history. The term is used to contrast such a body with differing rocks to which it is juxtaposed or by which it may be surrounded in whole or in part. The boundaries of a terrane are normally tectonic, i.e., faulted. In the present discussion "terrane" is used principally to characterize, collectively, the many areas of (1) ultrabasic harzburgite and (2) gabbro, both belonging to the ophiolite suite of rocks, and (3) the carbonate sedimentary rocks of the Ru′us Al Jibal.

Within the boundaries of the UAE, harzburgite (ultrabasic) bedrock is found primarily (i) in the Shimayliyah range of the East Coast; (ii) along the west flank of the mountains from Al Ghayl southwards, and especially from Wadi Shawkah south to Wadi Baraq (where the Oman border intervenes); and (iii) in the Hatta enclave of Dubai Emirate, including Jebel Hatta (see Chap. 2).

Fig. 6.10 This view in upper Wadi Zikt is typical of the harzburgite terrane of Shimayliyah: deeply incised wadis, thick gravel terraces and steep, rocky, rubble-covered slopes. Photo credit: Gary Feulner

6.2.1.3.1 The Shimayliyah Range

The rugged mountains of the Shimayliyah range, situated between the Gulf of Oman coast and the Dibba-Masafi-Fujairah roads, are composed almost entirely of harzburgite, representing a slice of the earth's uppermost mantle. This area includes all of Wadi Wurayah National Park (Wadi Wurayah and Wadi Zikt) and the relatively low, hilly region immediately south and west of Dibba Fujairah, as well as most of Wadi Madha and Wadi Shis, Wadi Shi, Wadi Safad, Wadi Deftah, uppermost Wadi Siji and uppermost Wadi Abadilah. The topography is typically very steep and rugged, generally culminating in narrow, rocky ridgetops (Fig. 6.10). Harzburgite weathers readily at the earth's surface and slopes are often littered with small, weathered chips, making ascents treacherous. Open slopes are poorly vegetated but along main wadis in harzburgite, gravel terraces ca. 10 m high are often well developed. Gullies on the rocky slopes and the boundary zone between lower slopes and gravel terraces are favored sites for plant growth (Fig. 6.11).

6.2.1.3.2 Ultrabasic Rocks and Botanical Diversity and Endemism

The extensive areas of harzburgite bedrock within the Hajar mountains present a challenging environment for most plants. Harzburgite has an unusual chemistry for

Fig. 6.11 Some characteristic plant species of harzburgite wadis, terraces and slopes: (**a**) *Convolvulus virgatus* (Convolvulaceae), a very common species in ultrabasic terrane. (**b**) Drumstick tree *Moringa peregrina* (Moringaceae). (**c**) *Gypsophila bellidifolia* (Caryophyllaceae), a diminutive wadi bed annual believed to favor ultrabasic terrane. (**d**) *Salvia macilenta* (Lamiaceae), a woody, perennial mint also believed to favor ultrabasic terrane. Photo credits: Gary Feulner

surface rocks, being very low in silica (SiO_2), calcium and aluminum, and very high in magnesium, iron and the heavy metals nickel, chromium and cobalt (Moores 2011; Kay et al. 2011). Geologists call this suite of chemical characteristics "ultrabasic" (or "ultramafic"). Soils in ultrabasic rocks are usually poorly developed, standard nutrients are scarce, the high magnesium levels interfere with uptake of calcium, and the heavy metals are toxic to many plants (Harrison and Kruckeberg 2008).

Groundwater percolating slowly in harzburgite bedrock reacts with the rock to become, over time, hyperalkaline (Moores 2011), with a long-term equilibrium pH in excess of 11 (Emirates Wildlife Society – WWF 2006). In places where such groundwater is reintroduced to surface water, it reacts immediately with atmospheric carbon dioxide (CO_2) to precipitate a surface film of calcium carbonate ($CaCO_3$). This creates the distinctive "white pools" sometimes seen in harzburgite areas, although that phenomenon is more common in the mountains to the south of the Madam-Hatta road, an area no longer readily accessible from the UAE.

Large ultrabasic terranes elsewhere in the world (e.g. in California, Cuba and New Caledonia) are well known for their low botanical diversity but also high endemism (Harrison and Kruckeberg 2008; Anacker 2011). Generally accepted information for six of the larger such areas globally puts their total number of "serpentine endemics" at from tens to many hundreds of species (Anacker 2011). This potential relationship between ultrabasic geochemistry, biodiversity and endemism has been all but totally ignored by botanists working in the mountains of the UAE and Oman, although it has sometimes been tacitly accepted as a generalization by local naturalists that the ophiolite terrane exhibits reduced plant diversity compared to other mountain environments (e.g., Munton 1985; Insall 1999). However, even those seemingly direct comparisons of ophiolite or ultrabasic terrane with, e.g., the Ru′us Al-Jibal or the (much better studied) Jebel Akhdar must be assessed critically, as they may often warrant adjustment for factors such as elevation, rainfall amount and timing, and human influence (Munton 1985).

The one UAE study that expressly considered the possible role of ultrabasic geochemistry on plant distribution (Feulner 2016) did not find reduced plant diversity in a large ultrabasic (harzburgite) area (Wadi Wurayah National Park, where more than 200 species were recorded) in comparison with a nearby large basic (gabbro) drainage area (Wadi Hiluw) (based on El-Keblawy (2011) as supplemented by the author's records). In comparison with the carbonate sedimentary rocks of the Ru′us Al Jibal range at comparable elevations, floral diversity in WWNP was reduced, but not greatly reduced.

To date, no UAE or Oman plant species have been confirmed to be restricted to the extensive ultrabasic terrane of the UAE/Oman mountains, best represented in the Western Hajar (the UAE and northernmost Oman). Some candidate species exist (see Sect. 6.2.1.3.3) but they are few in number and the burden of convincingly proving a negative by overland field work is formidable. In light of the oft-repeated findings of high plant endemism in large ultrabasic terranes (and especially serpentine/serpentinite) elsewhere, it is reasonable to ask why the UAE's ultrabasic rocks, being part of the world's largest such exposure, do *not* seem to exhibit similar botanical anomalies.

A possible explanation may lie in the fact that the ultrabasic terrane studied in the UAE, i.e., Wadi Wurayah, Wadi Zikt and surrounding areas in the Shimayliyah range (Feulner 2016), consists of relatively fresh, unaltered harzburgite, whereas the ultrabasic terranes studied elsewhere (see Anacker 2011) were more thoroughly altered to serpentine, often becoming effectively serpentinite, therefore more like the ophiolite exposures along the west flank of the Hajar Mountains in the UAE (see Sect. 6.2.1.3.4 below). However, this explanation remains speculative, as does the chemistry and plant physiology that might support it. Other explanations might lie in biogeographical history, including factors such as insularity.

An alternative possibility is that ultrabasic endemics are present within the Hajar Mountain flora but are sufficiently cryptic that they have not yet been distinguished by field work from their non-endemic congeners. The author has considered the possibility that bedrock geology, and ultrabasic endemism specifically, might account for the distribution of the three very similar *Geranium* species found in the UAE and Oman (*G. biuncinatum*, *G. mascatense*, and *G. trilophum*) but preliminary field work does not support that hypothesis.

A practical problem in this regard is that very few botanical investigators have worked in the mountain areas of the UAE or northern Oman, except in the carbonate rocks of the Jebel Akhdar, and almost none have indicated any sensitivity to the geological distinctions within the ophiolite rocks. The Western Hajar extends for more than 250 km to the northwest of the Jebel Akhdar, to the UAE border at Kalba and beyond, encompassing many very large wadis draining the mountains. Along the Batinah coast, these include, *inter alia*, Wadi Hawasina, Wadi Bani Umar, Wadi Shafan, Wadi Sarami, Wadi ʻAhin, Wadi Hilti, Wadi Jizzi and its upper tributaries, Wadi Bani Umar Al Gharbi, Wadi Fizh, Wadi Dab'ayn, Wadi Ragmi and Wadi Fayd. The majority of this vast area consists of ultrabasic terrane, yet the whole area has been all but completely ignored by Muscat-based naturalists, botanists and zoologists alike.

In the segment of the Western Hajar to the north of Al Khabourah and Wadi Hawasina, Oman, and continuing into the UAE, the less complicated geology makes it relatively easy to estimate the area of exposure of ultrabasic rocks by reference to the seminal geological map by Glennie et al. (1974). In that truncated segment, which amounts to a little more than half the ultrabasic terrane of the UAE/Oman mountains as a whole, a conservative minimum estimate of the area of the harzburgite bedrock is 4500 km^2—sufficient to offer ample scope for discovery.

6.2.1.3.3 Some Candidate Species for Ultrabasic Sensitivity

Notwithstanding the foregoing generalizations, field work over many years permits the conclusion that at least a small number of UAE mountain plants "avoid" the ultrabasic harzburgite, presumably because they cannot deal with its extreme geochemistry (Feulner 2016). These include the Hanging Caper *Capparis cartilaginea* (a very conspicuous species which avoids the ophiolite rocks altogether, including both harzburgite and gabbro) (Fig. 6.12a); the Desert Thorn *Lycium shawii* (Solanaceae) (Fig. 6.12b); and the small, bristly borage *Echiochilon persicum* (Boraginaceae). The prevalence of several other UAE plant species appears to differ significantly between harzburgite substrate and gabbro and/or carbonate substrate (Feulner 2016). Feulner (2011) highlighted a dozen common Hajar Mountain species that were absent or rare in the Ru′us Al Jibal. On the other hand, and perhaps not surprisingly, at least a few UAE species seem to "prefer" the harzburgite, among them the UAE/Oman endemic shrub *Pteropyrum scoparium* (Polygonaceae) (see Fig. 6.4a), the woody mint *Salvia macilenta* (Lamiaceae) (Fig. 6.11d), and the diminutive wadi bed annual *Gypsophila bellidifolia* (Caryophyllaceae) (Fig. 6.11c) (Feulner 2016).

Another UAE endemic, *Lindenbergia arabica* (Fig. 6.12c), appears to favor harzburgite terrane, but perhaps for edaphic (i.e., soil or substrate-related) reasons as much as geochemical ones. It is typically found perched near the bottom of the vertical walls of the thick gravel terraces that line many wadis in the harzburgite, and is presumably specialized to exploit groundwater flowing slowly downward through the ultrabasic terrace gravels.

Fig. 6.12 A number of UAE plant species appear sensitive to the unusual chemistry of the extensive ophiolite rocks of the Hajar Mountains: (**a**) The Hanging Caper *Capparis cartilagenia* is absent from areas of ophiolite rocks. (**b**) The Desert Thorn *Lycium shawii* (center foreground) avoids areas of the ultrabasic rock harzburgite, but thrives on gabbro terrane. However, because it is highly palatable to livestock, most larger plants have grown up in the shelter of other trees, usually *Acacia* or *Ziziphus*, as here. The roots of the specimen shown have also been parasitized by a broomrape, *Orobanche cernua*. (**c**) The UAE/Oman endemic *Lindenbergia arabica* (Scrophulariaceae) is found almost exclusively on the vertical walls of the thick gravel terraces that form in areas of harzburgite bedrock. Photo credits: Gary Feulner

6.2.1.3.4 The Western Foothills

Harzburgite bedrock is also present along much of the westernmost edge of the Hajar Mountains in the UAE from Al Ghayl southwards, where it forms low hills and ridges among broad wadis debouching onto the plains. There the harzburgite is often pervasively altered by hydration to a platy mineral called serpentine, and/or heavily veined with white and green veins of serpentine, chlorite and other minerals, and fractured on a fine scale, so that the rock can sometimes be picked apart by hand (Fig. 6.13). This deeply weathered harzburgite (or serpentinite, as the pervasively altered rock is called) is a very poor substrate for plant growth, although plants may grow in the wadis and in the outwash gravels that inter-finger with the bedrock ridges and constitute an extension of the Alluvial Plains ecosystem.

The western foothills, including the western margins of the gabbro interior, have been enormously disrupted by quarrying of both rock and gravel; by road building, dams, pipelines and power lines; by overgrazing and the expansion of farms; and by groundwater extraction. In places the former land surface has been lowered by 2 m or more. Thus it is difficult to know exactly what the vegetation of these areas may have looked like before the modern era.

Nevertheless, there remain present in these foothill regions, but not in the UAE mountains generally, distinctive species such as Leptien's Spiny-Tailed Lizard (Arabic: *dhub*) *Uromastyx aegyptia leptieni* and Bosc's Fringe-Toed Lizard *Acanthodactylus boskianus*, found here near the southeasternmost extent of its global range (Fig. 6.14); and the Dwarf Palm *Nannorrhops ritchieana*, here at the northwesternmost extent of its global range (Fig. 6.15). The prostrate *Schweinfurthia imbricata*, a UAE/Oman endemic, is also found in this area.

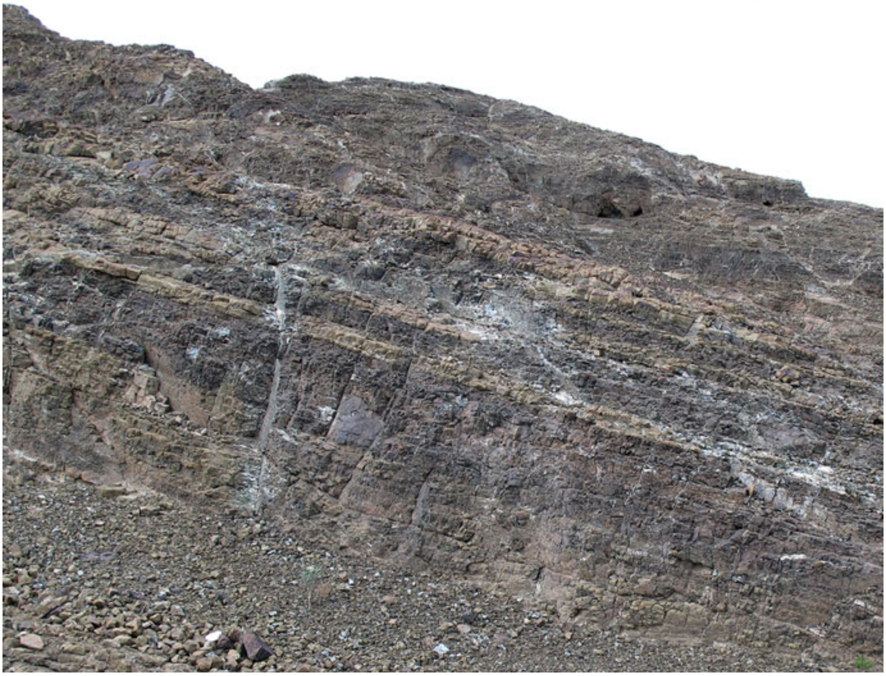

Fig. 6.13 Harzburgite bedrock exposed in the foothills along the west flank of the Hajar Mountains, near the base of the ophiolite slab, is often pervasively veined, foliated, fractured and altered to serpentine. It is sometimes mapped only as serpentinite. Photo credit: Gary Feulner

6.2.1.4 Gabbro Terranes

Gabbro rocks, part of the ophiolite suite of rocks and mostly representing former oceanic crust (Fig. 6.16), occupy much of the center and southeast of the Hajar Mountains in the UAE, south of the Dhaid-Masafi-Fujairah road (see Chap. 2). This includes, for example, all of Wadi Hiluw, upper Wadi Ashwani, upper Wadi Asfani (Wadi Baqarah), Wadi Sfai, Wadi Mayy, and lower Wadi Safad.

Topography in the gabbro terrane is rugged, as for the harzburgite, but weathering is less pervasive and fracturing is more blocky, resulting in somewhat more navigable, less precipitous terrain (Fig. 6.17). Gabbro chemistry is also more typical of surface rocks, equivalent to that of basalt produced by many oceanic and other volcanoes. As a result, gabbro areas are home to almost the full range of Hajar Mountain plant species (Fig. 6.18), including most of the species identified above that demonstrably avoid ultrabasic bedrock, as well as a number of species not yet recorded in the ultrabasic rock but which are too uncommon and/or too much restricted to higher elevations to allow us to insist that they are ultrabasic avoiders; examples of the latter include *Fagonia schimperi* (Zygophyllaceae) and the Mountain Mallow *Abutilon fruticosum* (Malvaceae).

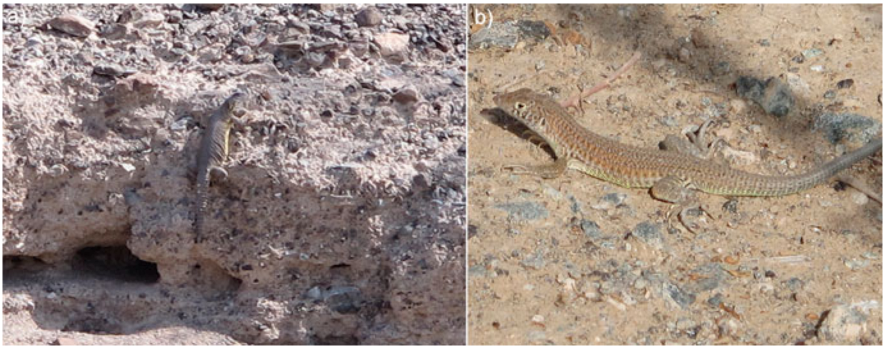

Fig. 6.14 The foothills in the southwest of the UAE mountain areas, including both harzburgite and gabbro bedrock, are home to two rare reptiles threatened by habitat destruction and overgrazing: (**a**) Small foothills populations of Leptien's Spiny-Tailed Lizard (or Dhub) *Uromastyx aegyptia leptieni* between Siji and Asfani are surrounded by an increasing number of livestock farms which decimate the local vegetation on which the dhubs depend, and they have lost habitat to routes for two major highways and a pipeline. Not surprisingly, their numbers appear to have declined. (**b**) Bosc's Fringe-Toed Lizard *Acanthodactylus boskianus* (female shown here) has not been recorded in recent years from sites on the alluvial plains, but has been discovered in two wadi environments that have been largely sidelined by development, where they seem to be able to tolerate a limited level of picnicking and agricultural activity in their immediate vicinity (Roobas and Feulner 2013; Roobas et al. 2014). Photo credits: Gary Feulner

In particular, an area of 1000 m gabbro ridges southwest of Fujairah City, that has been called the Olive Highlands, is home to a number of noteworthy plant and animal species not recorded in the harzburgite (Feulner 2014). They include, among others (see Fig. 6.19), *Ehretia obtusifolia* (Boraginaceae) and *Grewia tenax* (Tiliaceae), both edible large shrubs/small trees found most often where they are protected from grazing by terrain or by other vegetation; *Melhania muricata* (Malvaceae, formerly Sterculiaceae), the presumptive larval foodplant of a butterfly that lives in the highlands (the Arabian Grizzled Skipper *Spialia mangana*) and is a relict species itself; and most notably the wild olive tree *Olea europaea* (Oleaceae), which survives there in part because the northeast-facing cliffs of the Olive Highlands trap moist air from the Indian Ocean and promote enhanced fog and precipitation (Fig. 6.20). It was also in the Olive Highlands that the Persian Horned Viper *Pseudocerastes persicus* (Fig. 6.19d) was first recorded from the Hajar Mountains of the UAE, although its discovery spurred further investigation and it has since been found more widely (see Chap. 16).

6.2.1.5 Metamorphic Terranes

Within the ophiolite rocks north of the Dhaid-Masafi-Fujairah road, two geological "windows" expose pale colored metamorphic rocks that lie structurally beneath the ophiolite. One window is centered on the Asimah-Tayyibah area (Fig. 6.21), the

Fig. 6.15 The Dwarf Palm *Nanorrhops ritchieana* can be found in all of the wadis in the southwest of the UAE's mountain areas, but these mark the northern limit of its Arabian range. Photo credit: Gary Feulner

other on Wadi Shis, in the upper reaches of the large Wadi Madha drainage. The rocks exposed in the windows were originally sedimentary rocks deposited on the edge of Eastern Arabia, but they were later metamorphosed by heat and pressure when subduction carried them under the advancing ophiolite. The metamorphic rocks are not only paler than the ophiolite and recrystallized from their original condition; they also typically show signs of internal contortion (Fig. 6.22).

More importantly from an ecological perspective, the metamorphic rocks are geochemically very different from the ophiolite rocks: they are much richer in silica (SiO_2), calcium and aluminum and more like "average" continental rocks globally. It should not be surprising, therefore, that the metamorphic windows have been found to be home to at least a few plant species that are either unknown or rare elsewhere in the UAE. These include the delicate but ornate *Commicarpus stenocarpus* (Nyctaginaceae), which is so far known only from the metamorphic rocks; *Chaenorrhinum rubrifolium* (Scrophulariaceae), whose range extends south to Masafi; *Hyoscyamus muticus* (Solanaceae), a large-leafed henbane that is rare outside the Asimah-Tayyibah window; and *Lactuca orientalis* (Asteraceae), a brittle, spiky dwarf shrub with rectilinear architecture and peeling green stems (Fig. 6.23).

Dianthus crinitus (Caryophyllaceae), one of the UAE's showier native flowers, is found at relatively low elevation in the metamorphic rocks around Tayyibah,

Fig. 6.16 Gabbro bedrock in Wadi Sfai. The gabbro that formed part of the oceanic crust is typically layered, with alternating bands of light (plagioclase) and dark (olivine) minerals. Gabbro often weathers in a blocky fashion. Photo credit: Gary Feulner

Fig. 6.17 Summit ridges in gabbro are somewhat less forbidding than those in harzburgite, and the slopes are more hospitable to vegetation. Shown here is Jebel Qitab in the Olive Highlands. The lower slopes are shown in Fig. 6.2, above. Photo credit: Gary Feulner

whereas it is otherwise known primarily from higher elevations in the Ru′us Al Jibal. Within the ophiolite terrane (harzburgite and gabbro), *D. crinitus* is known only from a pair of plants recorded in the harzburgite of Wadi Wurayah, but the specific

Fig. 6.18 Some distinctive plant species of Hajar Mountain wadis, terraces and lower slopes. All except *Fagonia indica* are more or less equally common in harzburgite and gabbro terrane: (**a**) *Pulicaria glutinosa* (Asteraceae), very common on wadi banks and gravel terraces among the foothills. The dried bracts typically persist on the plant after the flowers have bloomed. (**b**) *Fagonia indica* (Zygophyllaceae), an erect shrub, yellow-green and usually bushy. All UAE *Fagonia* have four radiating spines at nodes along the stems. (**c**) *Physorrhynchus chamaerapistrum* (Brassicaceae), seen here growing profusely in silt behind a dam in Wadi Mayy. (**d**) *Cleome noeana* (Capparaceae), distinctively aromatic, often found as isolated specimens iin barren wadi gravel. (**e**) *Boerhavia elegans* (Nyctaginaceae) graces the landscape mostly in 'wet' years. (**f**) *Heliotropium calcareum* (Boraginaeae), the Octopus Heliotrope, most common on gravel terraces. (**g**) *Haplophyllum tuberculatum* (Rutaceae), another strongly aromatic species, the larval foodplant for the Common Swallowtail butterfly. Photo credits: Gary Feulner

site was within the weathered debris of one of a swarm of conspicuous white, granitic dikes that intrude the mountains overlooking the East Coast, so it may well be that *D. crinitus*, too, is sensitive to the bedrock geology of the substrate.

It is reasonable to suppose more generally that the less extreme geochemistry of the metamorphic rocks contributes to the success of the flourishing traditional agriculture within both of the geological windows. Unfortunately the native flora of most of the metamorphic areas has today been degraded or destroyed by the combination of extensive cultivation and overgrazing by domestic goats, except perhaps on the very steepest slopes above Wadi Shis.

6.2.1.6 Freshwater Bodies: Ponds, Pools, Streams and Seeps

6.2.1.6.1 Wadi Hydrology

Most of the rain that falls in the Hajar Mountains and is not carried off as floodwater is quickly concentrated in the coarse gravel wadi beds, where it flows within the interstitial pore space. At intervals along the wadi, where the gravel fill has been scoured or the bedrock has created an obstacle, small ponds or pools may form, sometimes connected by shallow streams that flow for tens or hundreds of meters

Fig. 6.19 Two distinctive residents of the Olive Highlands have been illustrated above, the Wild Olive *Olea europaea*, and the Arabian Grizzled Skipper butterfly *Spialia mangana* (see Fig. 6.5 a and d, respectively). Some other plant and animal species that distinguish the Olive Highlands include: (**a**) *Ehretia obtusifolia*, a large but often drooping shrub, is typically found in the shelter of Wild Olive trees or ledges; it is not found elsewhere in the UAE. (**b**) *Grewia tenax*, a rare and palatable large shrub / small tree that favors relatively mesic conditions and cliffs or ledges where it is protected from browsing quadrupeds. See also Fig. 6.38. (**c**) *Melhania muricata*, the probable larval foodplant of the relict Arabian Grizzled Skipper butterfly. (**d**) The Persian Horned Viper *Pseudocerastes persicus*, once thought to be very rare in the Hajar Mountains. This snake uses the tip of its tail as a lure to attract prey. Photo credit: Gary Feulner (a–c); Binish Roobas (d)

(Fig. 6.24; see Chap. 2). Some ponds, pools and stream reaches may be permanent but more often they are temporary.

These surface waters create a unique habitat within the context of arid Eastern Arabia: a home for aquatic organisms—a category that includes not only strictly aquatic organisms like fish, freshwater snails, flatworms and freshwater leeches, but also amphibious invertebrates such as diving beetles, water scorpions and the aquatic larvae of those and many other flying insects that breed in freshwater bodies, like dragonflies and damselflies, mosquitoes, caddisflies, craneflies and midges, as well as algae and higher plants (Fig. 6.25).

Fig. 6.20 The northeast-facing cliffs of the Olive Highlands trap moist air from the Indian Ocean and create increased fog and precipitation that support a high elevation "island" of biodiversity. Photo credit: Gary Feulner

Fig. 6.21 A panoramic view of the pale metamorphic rocks in the Asimah-Tayyibah area. Photo credit: Gary Feulner

Fig. 6.22 The metamorphic rocks exposed in the geological window at Wadi Shis often show internal contortion. They were deformed and recrystallized at depth when they were subducted under the advancing ophiolite. Photo credit: Gary Feulner

Fig. 6.23 Two of the otherwise rare plant species that are relatively common within the metamorphic terrane of the Asimah-Tayyibah area: (**a**) *Commicarpus stenocarpus*, so far recorded in the UAE only from this area, where it is locally common on slopes. (**b**) *Lactuca orientalis*, otherwise recorded only rarely at mid to high elevations in the Ru′us Al Jibal. Photo credits: Gary Feulner

Fig. 6.24 Some natural freshwater habitats in the Hajar Mountains: (**a**) A shallow gorge in Wadi Asfani, where permanent surface water (and the wadi fish *Garra barreimiae*) could still be found in recent years despite abstraction and the disruption of upstream areas by a major pipeline. (**b**) An exposed but well-vegetated permanent pool at the base of a small waterfall in a remote tributary of Wadi Asimah. The vegetation has since been cleared to facilitate use of the pool for a small farmstead on an adjacent terrace. (**c**) Extended temporary pools along the wadi track to the Wadi Wurayah waterfall, seen here during the "wet" years of the mid-1990s. (**d**) A sheltered temporary pool scoured at the base of a small waterfall in a tributary of Wadi Wurayah. Calm, shaded pools like this attract diverse diurnal flying insects, especially in hot weather. (**e**) A permanent pool near Hatta, home of the last known UAE population of the Hajar Lotak *Cyprinion mascatense*, a wadi fish now extinct in the Emirates. The site was destroyed by ill-considered construction of a recreational road. (**f**) Intermittent surface rivulets above the Wadi Wurayah waterfall, following major flooding that decimated the reeds that had previously clogged the wadi bed. (**g**) A small "slot" pool in upper Wadi Wurayah. These modest oases provide not only water but also critical habitat to wadi residents such as the endemic damselfly *Arabineura khalidi* (see Fig. 6.4g). (**h**) Sometimes the water table in a "dry" wadi may be very close to the surface. Humans have learned to exploit this phenomenon by making shallow scrapes to obtain clean fresh water. Evidence suggests that feral donkeys may also have acquired this skill. Photo credits: Gary Feulner

Fig. 6.25 Freshwater animal life in Hajar Mountain wadis: (**a**) Striped Predaceous Diving Beetle *Hydaticus* (*Prodaticus*) *histrio* (Coleoptera: Dytiscidae). (**b**) Polka Dot Predaceous Diving Beetle *Hydaticus* (*Prodaticus*) *pictus* (Coleoptera: Dytiscidae). (**c**) Aquatic larva of a predacous diving beetle (Coleoptera: Dytiscidae); the larvae are considered fierce predators. (**d**) Water Scorpion *Laccotrephes fabricii* (Hemiptera: Nepidae). This shallow water bottom dweller hunts with its pincers, usually by ambush. The long 'stinger' is not a weapon but a paired breathing tube. (**e**) Backswimmer *Notonecta* sp. (Notonectidae). This insect floats up to 30 cm below the water surface, belly up, and attacks unsuspecting surface prey. (**f**) Caddisfly larvae (Order Trichoptera). The species shown here is rather large and makes its protective "shell" by cementing sand grains. Photo credits: Gary Feulner (a,d–f); Tamsin Carlisle (b,c)

6.2.1.6.2 Mobile Cosmopolitan Species

Many, perhaps most, of the flying insects and most of the water plants and algae that inhabit these freshwater bodies are mobile cosmopolitan species that are able to colonize favorable habitats over broad geographic ranges (van Harten 2008, 2009, 2010, 2011, 2014, 2017; D.M. John, pers. comm.). UAE freshwater snails achieve the same result by relying on other organisms such as birds and perhaps even large flying insects to disperse their eggs or young. That assistance is critical because none of the UAE's native snails can survive extended desiccation at any stage of their life cycles. The most common UAE freshwater snail is the long, conical *Melanoides tuberculata* (Thiaridae) which produces live young by parthenogenesis; it is found in all the countries bordering the Indian Ocean and has become invasive globally (Feulner and Green 1999), but its pedigree in Eastern Arabia goes back to at least the pluvial lakes of the Pleistocene (McClure 1984). The largest and most typical vascular plants associated with water—e.g. Oleander *Nerium oleander*

Fig. 6.26 Freshwater plants in Hajar Mountain wadis: (**a**) Oleander *Nerium oleander*. An extensive grove in a "wet" tributary of Wadi Fay, Fujairah. The tributary is distinctive by being situated in an outlier of tectonized harzburgite and having remarkably limited floral diversity. (**b**) Giant Reed *Arundo donax*. Although native to the Middle East, this reed has a global reputation as an invasive species. (**c**) Common Wadi Grass *Saccharum griffithii*. A distinctive and characteristic species of Hajar Mountain wadi beds, this species requires a certain amount of subterranean wadi flow. (**d**) Southern Cattail *Typha domingensis*. Widespread globally in the tropics and subtropics, it is rare in the UAE because it requires more or less permanent, still surface water. (**e**) Filamentous pond algae, probably *Spirogyra* sp., growing in a temporary pond formed where an earthen road crossing dammed a shallow wadi. The algae grows first as thin, slimy green filaments, but if growth is profuse, it forms cloud-like mats at the surface and can deplete the water of nutrients available to other organisms (D.M. John, pers. comm.). Photo credits: Gary Feulner

(Apocynaceae), the Giant Reed *Arundo donax*, the common Wadi Grass *Saccharum griffithii*, and the Southern Cattail *Typha domingensis* (all Poaceae) (Fig. 6.26)—appear to rely most heavily on wind dispersal of their seeds (see also Chap. 13).

6.2.1.6.3 Isolation and Speciation of Freshwater Fishes

For fully aquatic or non-migratory animal species, both vertebrate and invertebrate, the dispersed and only intermittently connected freshwater bodies of the Hajar Mountains are like islands, each having its own population, which, over time, can diverge and result in the creation of new subspecies or even new species. This has not been demonstrated within the UAE proper, but within the UAE/Oman mountains as a whole, it has recently been shown by genetic studies that the scattered populations of the most common and widespread wadi fish, heretofore treated as several subspecies of *Garra barreimiae*, actually represent five unique species of *Garra*, each occupying geographically distinct major watersheds draining the high mountain areas of Northern Oman (Pichler et al. 2018; Freyhof et al. 2020; Kirchner et al. 2020).

As one result, only the *Garra* populations of the Western Hajar, to the northwest of the Jebel Akhdar, retain the scientific name *G. barreimiae*; this includes the fish populations on both flanks of the mountains in the UAE and northernmost Oman. Mixing of the *G. barreimiae* populations on both the interior and Gulf of Oman flanks was probably facilitated by drainage patterns like that of Wadi Jizzi, which begins in the interior near Al Ain and Buraimi and breaches the mountains to reach the Gulf of Oman north of Sohar; and of the Wadi Hatta corridor, where Wadi Hadf, the uppermost major tributary of Wadi Hatta, once fed outwash channels that flowed to both the Arabian Gulf and the Gulf of Oman (Feulner 1999a).

6.2.1.6.4 Freshwater Bodies as a Community Resource

Wadi pools and streams are important as a resource even for non-aquatic wadi life, both vertebrate and invertebrate. Birds, lizards, snakes, bees and other flying insects can all be seen coming to drink from time to time. In most cases the presence of surface water enlarges the size of the populations that an area can support, which in turn has ecological effects of its own. For example, the Wadi Racer *Platyceps rhodorachis*, probably the most commonly encountered mountain snake, often hunts submerged in shallow wadi pools to ambush *Garra*. Similarly, the Hajar Saw-Scaled Viper *Echis omanensis*, which often lies in wait beside mountain pools and streams, has come to treat the abundant wadi toads, the Arabian Toad *Sclerophrys arabica*, as a principal food resource, despite the fact that toads are normally disfavored by vipers as prey due to the noxious chemicals produced by their skin glands. *E. omanensis* can also turn the arid Hajar Mountain environment to its advantage by preying on fish trapped in drying puddles.

Among invertebrate predators, Grass Spiders or Water Orb-Weavers (Tetragnathidae) hunt from webs suspended horizontally over pools and streams (Feulner and Roobas 2015); a tiger beetle (*Lophyridia fischeri elongatosignata*) and a common UAE wolf spider (a still-to-be-described species of *Wadicosa*; T. Kronestedt, pers. comm.) are specialized hunters on damp ground beside wadi pools and streams (Fig. 6.27). The majority of UAE dragonflies and damselflies are hawkers or darters at freshwater habitats of one sort or another in the mountain environment (Feulner et al. 2007; Reimer et al. 2009).

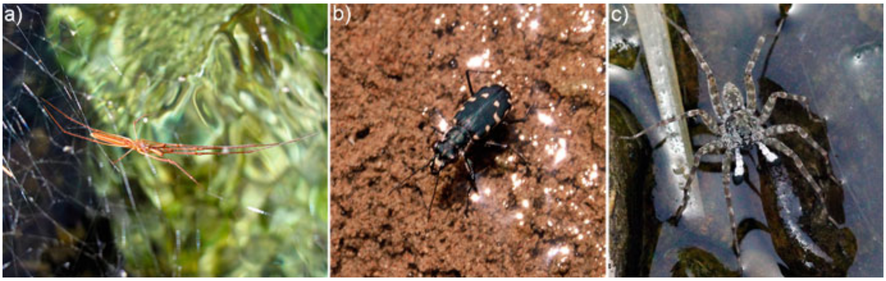

Fig. 6.27 Some invertebrate predators found at mountain pools: (**a**) The large local Grass Spider *Tetragnatha* sp. (Tetragnathidae) hunts from a web constructed horizontally over flowing water. If the spider happens to fall in the water, it can swim out quickly, but very inelegantly. (**b**) The tiger beetle *Lophyridia fischeri elongatosignata* hunts on damp ground beside pools. It is very skittish and takes flight at the first sign of approach. Normally bronze-brown in color, a rare blue-green specimen is shown here. (**c**) The wadi wolf spider male shown here is very common on gravel beside pools and streams; the female is often seen carrying her egg sac by her spinnerets. They can escape predators by running on water. Tentatively identified by Feulner and Roobas (2015) as a *Pardosa* sp., this spider is now understood to be a new species of *Wadicosa*, awaiting description (see text). Photo credits: Gary Feulner (a,b); Binish Roobas (c)

6.2.1.6.5 Physical Parameters of Wadi Water

Few published studies are known to exist of the physical parameters of surface water in the Hajar Mountains of the UAE, including possible geographical, geological, seasonal or episodic variability. An ad hoc survey of ca. two dozen sites in Wadi Wurayah from January to March 2006, including both "pools" and "riffles" of various descriptions, provides some indicative data reported by Emirates Wildlife Society—WWF (2006) and Tourenq et al. (2011). Water temperature was found to vary between ca. 22 to 28 °C. pH was slightly alkaline, said to average 8.3 with a range of ca. 8.2 to 9.1. Average dissolved oxygen varied between 5.2 and 11.22 mg/liter. Nitrate concentrations ranged from 4.6 to 7.8 mg/liter, averaging 5.76 mg/liter.

6.2.1.6.6 Freshwater Seeps

Freshwater seeps are found occasionally along Hajar Mountain wadi walls, almost always in harzburgite terranes, where gravel outwash sediments overlie bedrock or where poorly cemented sediments overlie a more thoroughly cemented layer (Fig. 6.28). They are also found today in anthropogenic settings, e.g. below a leak or frequent overflow from a falaj irrigation system. These seeps, where groundwater dripping from the overlying source dampens the rock face below with a thin film of water, are the typical habitat of the Maiden's Hair Fern *Adiantum capillus-veneris*.

Seeps that are larger or more reliable may also host, among the more numerous ferns, small numbers of *Epipactis veratrifolia* (Orchidaceae), a helleborine orchid found in marshy environments from Turkey and Somalia in the west to south China

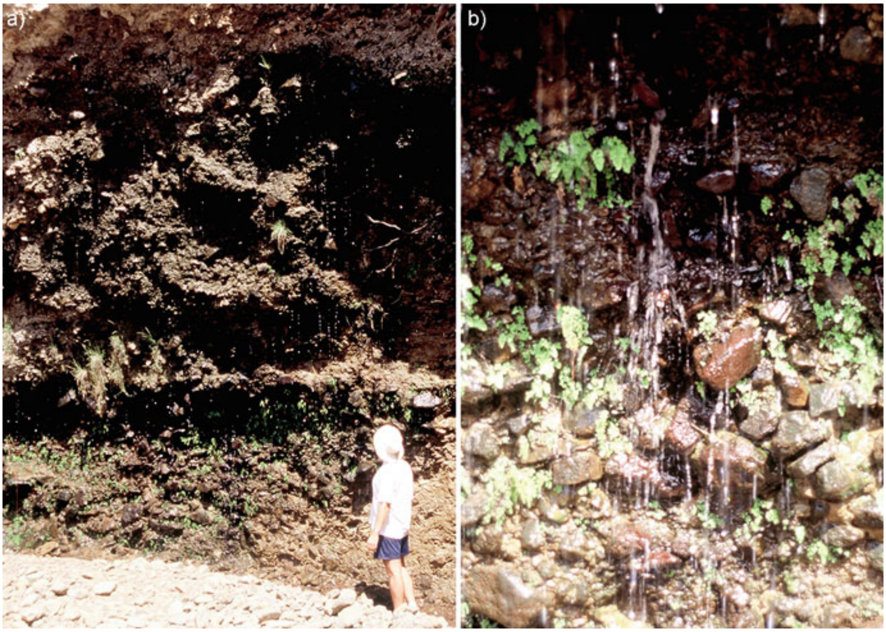

Fig. 6.28 (**a**) A "weeping wall" in ophiolite terrane near Hatta. The groundwater is exiting the wadi wall along a horizon where the upper gravels are underlain by a better-cemented unit. (**b**) The Maiden's Hair Fern *Adiantum capillus-veneris* is seen here in its typical UAE habitat. Toads can sometimes be found on walls like this. Photo credits: Gary Feulner

in the east. Because it is the UAE's only orchid, *E. veratrifolia* has understandably attracted special attention and concern for its welfare, to an extent that other rare or potentially threatened species can only dream of achieving. But in fact, the orchid's natural sites are under threat primarily from the possibility that global climate change will reduce rainfall in UAE mountain areas, which is by no means certain. In any case, anthropogenic activities have, on balance, probably created as many or more potential habitats as they have destroyed, although this might not continue if greater attention is paid to efficient water use and repair of leaky irrigation infrastructure.

6.2.1.6.7 Flooding in the Wadis

Flooding in mountain wadis (Fig. 6.29) is infrequent but consequential. It is necessary to the health of the ecosystem but, like fire in a savannah, it is also disruptive. When rain begins, it quickly accumulates in rivulets on slopes and depressions on terraces. In small tributary wadis the flow is shallow but turbulent, the waters opaque with sediment. These often take a final, steep plunge into the main wadis, where, at first, little seems to happen. The brown waters spread out in a small fan over the

Fig. 6.29 Some examples of UAE mountain wadis in spate: (**a**) Wadi Asfani, filling slowly after a thunderstorm in October 1997. Within half an hour the entire wadi bed shown here was flooded. (**b**) Wadi Sfai, flooded after modest rain in December 1998. In this instance, the waters receded enough for cars to pass comfortably after about 2 h. (**c**) Flooding at the Wadi Wurayah waterfall in December 2012. Moderate rain had fallen for an hour without affecting the main wadi, but about 45 min later the waterfall wadi and adjacent tributaries draining from the north and west began to spout brown, foaming water. (**d**) Whitewater in Wadi Ayim gorge, near Al Ghayl, in February 1993. There is no permanent surface water in this area. Photo credits: Gary Feulner (a,b,d); Jacky Judas (c)

gravel wadi bed, and sink in, filling the often substantial pore space in the surface gravels.

But then, if the rainfall continues, a threshold is crossed. The pore space in the wadi gravel is filled, after which every additional drop that reaches the wadi becomes part of the surface flow, which quickly builds and accelerates. Where wadis are relatively broad, floodwater depth in the modern era is estimated generally to be no more than about a meter to a meter and a half, based on flotsam and visual observation. In gorge areas, however, the choked waters can rise to many meters, sometimes overtopping the dramatic channels incised in cemented gravels.

The creatures resident in the wadis seem to be adapted to these flood events, as they must be, but occasionally one finds dead snakes or small mammals in their wake, and the floodwaters invariably transport and aggregate the abandoned shells of local land snails, sometimes surprisingly abundant. Naturalist observers who have overnighted in heavy rain in the mountains have reported another hazard, that of falling rocks and stones dislodged by the rain and consequent erosion.

If rainfall does not continue, most floodwaters recede within hours to days, but pools and streams in the gravel wadi beds may be refreshed for weeks or months.

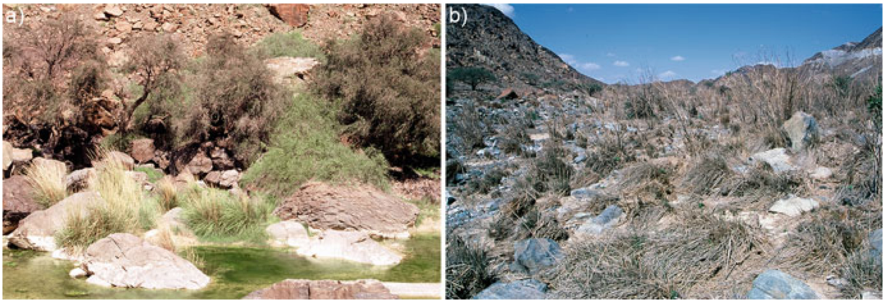

Fig. 6.30 How permanent is "permanent"? To understand Hajar Mountain ecosystems, a certain amount of patience may be required. (**a**) This photo shows a site along lower Wadi Hiluw with unusually large, old trees. It was taken in March 1996, during the very "wet" years of the mid-1990s (see Feulner 2006), when flooding destroyed power pylons and for several years the lower wadi featured intermittent surface pools and small streams year-round, with localized populations of the Arabian Killifish *Aphanius stoliczkanus*, a euryhaline species common in coastal lagoons. The wadi ecosystem was anomalous, however, in that the principal native wadi fish of the Hajar Mountains, *Garra barreimiae*, was absent (Feulner 1998). This was an indication that things were not what they seemed. Subsequent monitoring since 1999 has confirmed that Wadi Hiluw does not normally support year-round surface water. The killifish had been introduced for mosquito control—a practice which continues in mountain areas, both officially and unofficially. (**b**) The same phenomenon, including the introduction of Arabian Killifish, was confirmed for Wadi Baraq on the west flank of the mountains, where extensive stands of hygrophilic vegetation that prospered during 1995 to 1998 (Oleander, Common Wadi Grass, Mountain Bulrush and even Southern Cattail) were left to wither and die over the ensuing years, as seen here. Photo credits: Gary Feulner

The heavy rains of the mid-1990s (Feulner 2006) were sufficient to create conditions of extensive year-round surface water in several wadis that, it is now known, do not otherwise sustain it in the modern era. It may or may not be a coincidence that each of those wadis was in gabbro terrane (Fig. 6.30); in at least one case abstraction for agriculture is likely to have played a significant role in depleting the surface flow. The foregoing nothwithstanding, the map of wadi fish distribution in Feulner (1998, Fig. 6.1 at page 22), although not fully comprehensive, has often been used as a surrogate for a census of the UAE and northernmost Oman wadis that have permanent surface water. It is nevertheless difficult to identify the precise conditions that differentiate wadis with permanent surface water from those without. A striking example is the contrast between Wadi Wurayah, known for its year-round waterfall and upstream "wet" gorges, and its similarly-sized northern neighbor, Wadi Zikt (both within Wadi Wurayah National Park), where no permanent surface water has yet been discovered.

6.2.2 *The Ru′us Al Jibal (the Mountains of the Musandam)*

The Ru′us Al-Jibal comprises a thick (3000 m) sequence of pale grey to pale tan carbonate sedimentary rocks (limestone $CaCO_3$ and dolomite $CaMg(CO_3)_2$) that

Fig. 6.31 An exhilarating panorama of the high Ru′us Al Jibal, overlooking Wadi Naqab from Silhi in the south-central Ru′us Al Jibal, photographed in the mid-1990s. Just visible on the horizon to the north are Jebel Rahabah and Jebel Jais. Photo credit: Gary Feulner

were vertically elevated in geologically recent times. The physiognomy of the Ru′us Al Jibal is characterized by "square" or blocky profiles, with steep cliffs and flat, plateau-like summits (Fig. 6.31). The carbonate rocks are karstic, so, among other things, they are full of subterranean solution channels and there is little surface or near surface water. Consequently plants that depend on interstitial flow in wadi gravels, like Oleander *Nerium oleander* or Wadi Grass *Saccharum griffithii*, are all but absent from the Ru′us Al Jibal, although both are common in the Hajar Mountains (Feulner 2011).

As an exception to the rule, a few wadis in the Ru′us Al Jibal feature "pothole" pools scoured in bedrock. These may be relatively deep and, where they are shaded, they can retain water for substantial periods of time and so become magnets for birds and flying insects, as well as freshwater snails carried in adventitiously as sticky egg masses or clinging neonates. Their steep, smooth sides make many such pools difficult, even treacherous, for quadrupeds to access, but it is probably not a coincidence that the narrow defile of Wadi Zibat, which contains a chain of bedrock pools, accounted for many of the last reported sightings and traces of the Arabian Leopard in the Musandam region (Fig. 6.32).

Vegetation in the Ru′us Al Jibal is generally concentrated on wadi banks as well as in and along ravines and gullies on rocky slopes and plateaux (Fig. 6.33). Even on intermediate slopes, the Ru′us Al Jibal flora includes elements not generally seen in the Hajar Mountains, for example, the colorful but spiny *Astragalus fasciculifolius*

Fig. 6.32 Pothole pools in the formidable gorge of Wadi Zibat, thought to be a last refuge of the Arabian leopard in the Ru′us Al Jibal because water could be found there. Photo credit: Gary Feulner

(Fabaceae), *Fagonia schimperi* (Zygophyllaceae), *Farsetia aegyptia* (Brassicaceae) and the plume grass *Stipagrostis paradisea* (Poaceae) (Fig. 6.34). The high elevation flora of the Ru′us Al Jibal, above ca. 1100 m, is characterized by Irano-Turanian species that are absent or very rare elsewhere in the UAE—almond trees *Prunus arabica* (Rosaceae) [listed in Jongbloed et al. (2003) as *Amygdalus arabica*] and *Artemisia* steppe, dominated by dwarf shrubs and grasses, particularly the wormwood *Artemisia sieberi* (Asteraceae) [listed in Jongbloed et al. (2003) as *Seriphidium herba-alba*], the spiny *Convolvulus acanthocladus* (Convolvulaceae), the lemon grass *Cymbopogon jwarancusa* (Poaceae), the gymnosperm *Ephedra pachyclada* (Ephedraceae) and the spiky-budded *Centaurea wendelboi* (Asteraceae) (Figs. 6.35 and 6.36). Notably absent at high elevations is *Euphorbia larica*, one of the most common and characteristic shrubs of slopes and plateaux at low and medium elevations; unfortunately this significant fact has sometimes been misrepresented in print (e.g. Llewellyn-Smith 2002).

Fig. 6.33 Abundant vegetation in a bedrock gulley not far from Jebel Yibir. Photo credit: Gary Feulner

As to fauna, the Ru′us Al Jibal has recently been shown to have a number of its own endemic geckoes (*Ptyodactylus* and *Asaccus* spp.; Burriel-Carranza et al. 2022). Only Dhofar Toads *Duttaphrynus dhufarensis* are found in the interior of the Ru′us Al Jibal, not the more gregarious and water-loving Arabian Toad *Sclerophrys arabica* (Cunningham and Feulner 2001). Above about 700 m, the high Ru′us Al Jibal is home to two tiny land snails otherwise known only from more northerly regions: *Gibbulinopsis signata* (which ranges from Turkey to Central Asia) and *Granaria persica* (also found in the southern Zagros Mountains in Iran) (Feulner and Green 2003). Both snails are considered to be relicts of a more mesic climate in the UAE. The same is true of the two-centimeter land snail *Mordania omanensis*, found today only at high elevation in the Ru′us Al-Jibal and the Jebel Akhdar (see Fig. 6.5e).

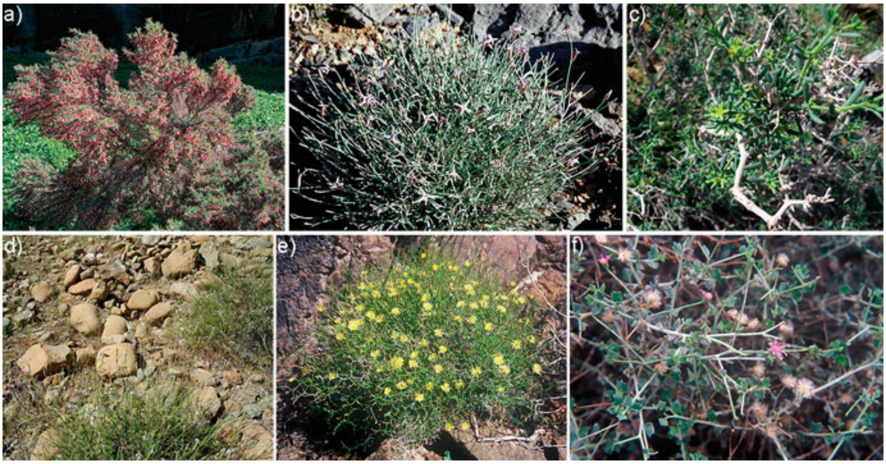

Fig. 6.34 Some typical plant species of Ru′us Al Jibal slopes at intermediate elevation: (**a**) *Astragalus fasciculifolius* (Fabaceae). (**b**) *Farsetia aegyptia* (Brassicaeae). (**c**) *Gymnocarpus decandrum* (Caryophyllaceae). (**d**) *Lavandula subnuda* (Lamiaceae). (**e**) *Launaea bornmuelleri* (Asteraceae). (**f**) *Vernonia arabica* (Asteraceae). Photo credits: Gary Feulner

6.2.2.1 Cliff Environments

Mountain areas provide opportunities for cliff-dwelling plants or chasmophytes. Cliffs, defined operationally as rock surfaces over 2 m in height and sloping at an angle of more than 60°, are widespread in the UAE/Oman Mountains, and especially so in the Ru′us Al Jibal. Globally, they represent one of the least disturbed habitat types and therefore often contain extensive areas of natural vegetation. Studies of cliff vegetation are difficult for a number of practical and theoretical reasons, but it has been shown from other parts of the world that cliffs harbor some of the most floristically diverse communities, and cliff habitats therefore often contribute substantially to biodiversity, more than their actual surface extent would suggest (Larson et al. 2000).

In the UAE, cliff-dwelling species include prominently two large hanging shrubs: (i) *Capparis cartilaginea* (Capparaceae) (see Fig. 6.12a) is common on cliffs at low elevations in the Ru′us al Jibal and is a dominant species on Jebel Hafeet, but is conspicuously absent from the ophiolite rocks in between; (ii) *Cocculus pendulus* (Menispermaceae) (Fig. 6.37) is also common in the Ru′us Al Jibal and present, but rarer, in the Hajar Mountains (Jongbloed et al. 2003, Feulner 2011). The smaller Common Caper *Capparis spinosa* is found most often as a cliff-dwelling shrub at low and medium elevations in both the Hajar Mountains and the Ru′us Al Jibal (Jongbloed et al. 2003, Feulner 2011, 2016). The diminutive *Rosularia adenotricha* (Scrophulariaceae) is found only in sheltered limestone hollows high in the Ru′us Al Jibal (Feulner 2011). The Wadi Fig *Ficus salicifolia* (Moraceae)and the wispy

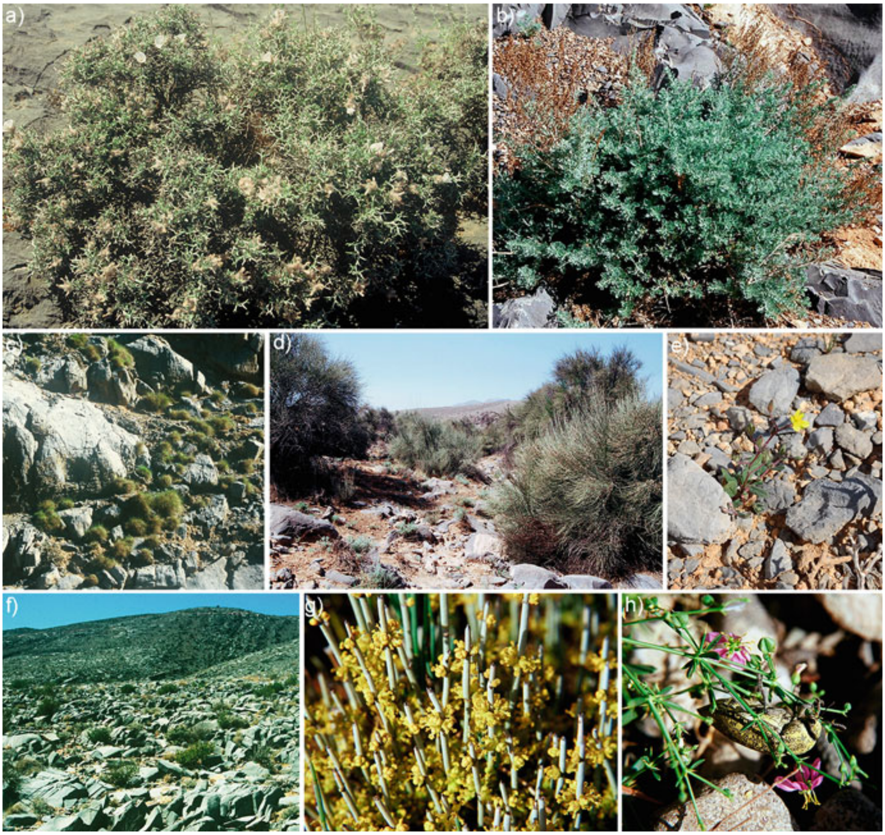

Fig. 6.35 Some typical plant species of Ru′us Al Jibal plateaux at high elevation, mostly Irano-Turanian species: (**a**) *Convolvulus acanthocladus* (Convolvulaceae), dominant in many exposed areas. (**b**) *Artemisia sieberi* (Asteraceae) (formerly *Seriphidium herba-alba*), new leaves (green) flourishing among older dry growth (brown). (**c**) *Cymbopogon jwarancusa* (Poaceae), cushions on a hillside at ca. 1200 m. (**d**) Arabian Almond *Prunus arabica* (Rosaceae) (formerly *Amygdalus arabica*) along a gentle wadi at ca. 1500 m. (**e**) *Helianthemum salicifolium* (Cistaceae), a diminutive high elevation annual. (**f**) *Dodonaea viscosa* (Sapindaceae), stunted shrubs among limestone pavement at 1600+ m. (**g**) *Ephedra pachyclada* (Ephedraeae), one of the UAE's only two gymnosperms, on a gravel plain at ca. 1600 m. (**h**) *Fagonia schimperi* (Zygopyllaceae), a poorly known high elevation *Fagonia* species, shown here with a Sulfurous Jewel Beetle. Photo credits: Gary Feulner

Drumstick Tree *Moringa peregrina* (Sapindaceae) can also occur as cliff-dwellers, but they are limited to low or medium elevations.

Several other UAE mountain plants are found primarily in cliff environments, not because that is their primary habitat, but because it is the only place where they can survive the often-substantial local browsing pressure. For those plants, cliffs serve as refugia. Species in this category include the rare UAE/Oman endemic *Rumex limoniastrum* (Polygonaceae); the large shrubs/small trees *Cordia quercifolia* (Boraginaceae) [listed in Jongbloed et al. (2003) as *C. sinensis*], *Ehretia obtusifolia*

Fig. 6.36 Winter in the Ru′us Al Jibal: The author and colleagues at ca. 1800 m, near the summit of Jebel Jais, in January 2019. At right is stunted *Prunus arabica*, at left is *Ephedra pachylada*. The dominant vegetation cover is the dwarf shrub *Artemisia sieberi*, here dry and brown. Photo credit: Gary Brown

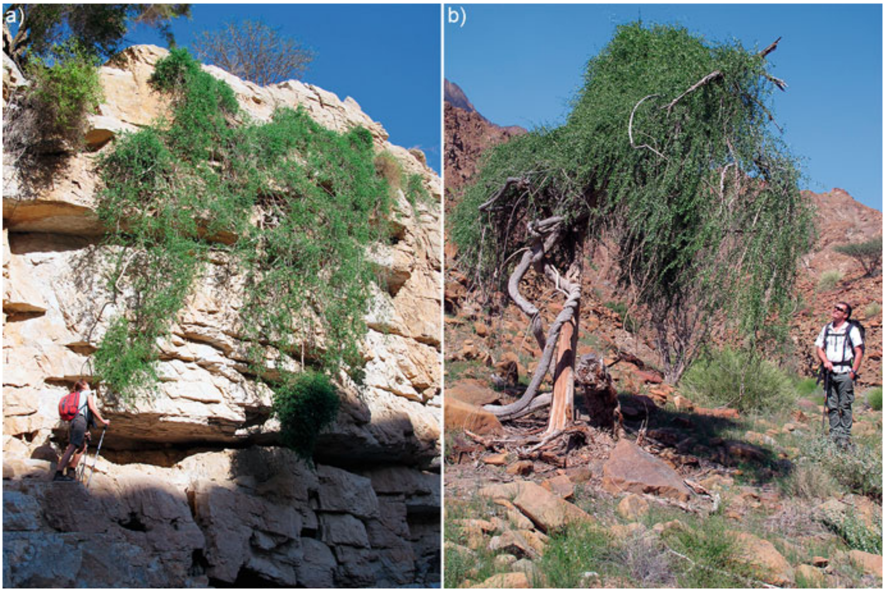

Fig. 6.37 *Cocculus pendulus* (Menispermaceae) can grow to be a very large hanging or climbing plant. (**a**) In the Ru′us Al Jibal it is locally common and is typically found on cliffs, as here in Wadi Naqab. (**b**) In the Hajar Mountains it is less common and is mostly a climber on Samr and Sidr trees, as here in a tributary of Wadi Wurayah. Photo credits: Gary Feulner

(Boraginaceae) (see Fig. 6.19a), *Grewia tenax* (Tiliaceae) (Fig. 6.38); and the dwarf shrub *Phagnalon schweinfurthii* (Asteraceae).

Cliff environments also create small sheltered nooks where limited amounts of soil can accumulate and moisture can be retained. These permit the establishment of more delicate, less dry-adapted species like two of the UAE's few ferns, *Cheilanthes pterioides* and *Cheilanthes vellea* (Adiantaceae), both diminutive, and tiny herbs like *Asterolinon linum-stellatum* (Primulaceae) and *Galium setaceum* (Rubiaceae); the latter also prospers under the skirts of larger shrubs.

One animal that depends on shaded microenvironments is the White-Edged Rock Brown butterfly *Hipparchia parisatis*, a large Palearctic mountain species that still keeps its Palearctic schedule, even in the UAE (Larsen 1983; Feulner et al. 2021) (see Fig. 6.5b). It emerges from the pupal state in mid to late March, but throughout the summer months it spends most of its daytime hours resting in the shade of cliffs, ledges and wadi banks, before breeding and dying in mid-autumn.

Fig. 6.38 In the UAE and adjacent northern Oman, *Grewia tenax*, normally a large shrub or small tree, is one of a number of mountain plants that is most often seen as a cliff dweller, because that is the most effective way to escape the often substantial local browsing pressure. See also Fig. 6.19b. At the top of the cliff is an Arabian almond *Prunus arabicus*. Photo credit: Gary Feulner

The rocky mountain environments of cliffs, ledges and boulders are also home to many of the diverse array of endemic reptiles summarized in the introduction to this chapter, particularly *Asaccus* spp., *Omanosaurus* spp., and *Ptyodactylus* spp. (see also Chap. 16).

6.2.3 The Dibba Zone

The Dibba Zone is a low and geologically diverse corridor that separates the ophiolite of the Hajar Mountains from the carbonate sediments of the Ru′us al-Jibal. The Dibba Zone rocks are a structurally discontinuous mix of deep and shallow water marine sediments and volcanics (Fig. 6.39) that were pushed ahead of the ophiolite as it was forced over the edge of the Arabian continent. The native flora has been heavily degraded by extensive cultivation and overgrazing by domestic livestock. The Dibba Zone is not considered to be distinctive from a botanical point of view, but one plant species, *Chesneya parviflora* (Fabaceae) (Fig. 6.40), is known in the UAE only from a handful of specimens recorded in the eastern half of the Dibba Zone (Feulner 2011, A. Gardner unpublished data). *C. parviflora* is otherwise known from the Makran, the hilly regions of southern Iran and Pakistan.

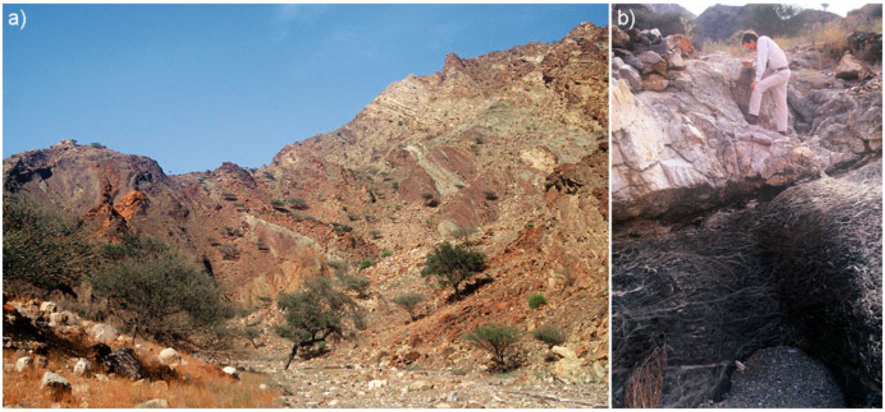

Fig. 6.39 (**a**). The multi-colored rocks of the Dibba Zone divide the carbonate sediments of Ru′us Al Jibal from the ophiolite rocks of the Hajar Mountains. They consist of a mix of tectonically jumbled rock units pushed ahead of the ophiolite while it was emplaced. (**b**) Most of the rocks found in the Dibba Zone are deep water sediments, but carbonate breccias and pillow lavas (seen here) are also present, probably representing former coral atolls. Photo credits: Gary Feulner

Fig. 6.40 *Chesneya parviflora* is known from the Makran region of Iran and Pakistan, and has also been found in the UAE, but so far only in the Dibba Zone. Photo credit: Drew Gardner

6.2.4 The Foreland Ridges (Jebel Hafeet et al.)

The Foreland Ridges are a discontinuous linear alignment of narrow, north-south trending, anticlinal ridges set about 20 to 25 km west of the main mountain front, and parallel to it (Figs. 6.41 and 6.42). At the surface, they expose latest Cretaceous and Paleogene shallow marine carbonate sediments deposited after the original emplacement of the Hajar Mountain ophiolite, but the forces that folded these later sediments are the same plate tectonic movements that caused the ophiolite emplacement in the first place: the continuing slow but inexorable convergence of the Arabian plate with the Eurasian plate.

Jebel Hafeet is unique among the foreland ridges by virtue of to its great height (ca. 1200+ m) and overall size (15–20 km long), but it is also, by far, the southernmost of the mountain areas that are physically within the UAE. For that reason, Jebel Hafeet also partakes of the broader biogeographical changes that are related to latitude, discussed in more detail at Sect. 6.3.1 below.

The foreland ridges have long been noted for their relatively depauperate flora, but also for the presence of plant species that are rare or absent elsewhere in the UAE, e.g. *Capparis cartilaginea* (Capparaceae) (see Fig. 6.12a), *Dipcadi biflorum* (Liliaceae), *Heliotropium rariflorum* (Lamiaceae), and *Salsola rubescens* (formerly Chenopodiaceae, now Amaranthaceae) (Fig. 6.43). The first and last listed species are among the known ophiolite "avoiders".

A small number of the UAE's native plants and animals are found only, or primarily, on Jebel Hafeet or in its immediate vicinity; many of these, however,

Fig. 6.41 Jebel Hafeet, by far the largest of the UAE's foreland ridges, rises some 800 m from the plains south of Al Ain, to reach a height of more than 1200 m. Photo credit: Gary Feulner

Fig. 6.42 The foreland ridges of Jebel Faya and its neighbors (Jebel Buhais, Jebel Mleiha et al.) are located in Sharjah, but they are geologically analogous to Jebel Hafeet, and originated in the same way. They are seen here from the west, across Wadi Faya. Photo credit: Gary Feulner

Fig. 6.43 (**a**) *Dipcadi biflorum* (Liliaceae) and (**b**) *Heliotropium rariflorum* (Boraginaceae) are associated with the smaller, northerly foreland ridges in Dubai and Sharjah, while (**c**) *Salsola rubescens* (Chenopodiaceae) is found primarily on Jebel Hafeet, but there are also more northerly records. Photo credits: Gary Feulner

are more common southwards, in northern Oman. Plants in this category include *Acridocarpus orientalis* (Malpighiaceae) (Arabic: qafas) (Fig. 6.44); the chenopod (now Amaranthaceae) *Halothamnus bottae*; and the diminutive, prostrate *Herniaria maskatense* (Caryophyllaceae).

Animals in the same category include four butterflies found in the UAE primarily at or in the vicinity of Jebel Hafeet: the Desert Orange Tip *Colotes liagore* (Pieridae); the Yellow Pansy *Junonia cebrene* (Nymphalidae: Nymphalinae); the Giant Skipper *Pyrrhiades anchises* (Hesperiidae: Coeliadinae) and the Baluchi Ringlet *Ypthima bolanica* (Hesperiidae: Hesperiinae). Jebel Hafeet is also the only UAE location known to have continuously maintained a wild population of Arabian tahr *Arabitragus jayakari*.

6.2.5 The Alluvial Plains

The ecology of the gravel outwash plains is ultimately based on the supply of sediment and water from rainfall over the adjacent mountain areas, which reaches the plains via wadis and then traverses them, when flow is sufficient, via braided streams and sheet flooding. Much of this water supply will sink into the more-or-less porous gravels en route. Some will continue its passage towards the coastal regions via established underground channels; some will take up longer term residence as near surface ground water. During intervals of greater rainfall, these processes have been sufficient to maintain scattered lakes on the plains, or in the sands to the west, over periods of thousands of years, creating a sedimentary record of former climate and vegetation in the form of isotope geochemistry, pollen and phytoliths (Parker et al. 2004).

At times the alluvial plains have probably resembled savannah environments like those seen today in East Africa. Hints of such former conditions are best preserved on the plains adjacent to the Ru′us Al Jibal, inland of Ras Al Khaimah city, where stands of the Umbrella Thorn *Acacia tortilis* still create occasional visually

Fig. 6.44 (**a**) The Qafas plant *Acridocarpus orientalis* (Malpighiaceae) is found in the UAE exclusively at the north end of Jebel Hafeet, in upper Wadi Tarabat. It is much more common immediately to the south, in the mountains of northern Oman (shown here). (**b**) The distribution of the Giant Skipper butterfly *Pyrrhiades anchises* (Hesperiidae: Coeliadinae) is tied to that of *A. orientalis*, its exclusive larval foodplant. Photo credits: Gary Feulner (a); Binish Roobas (b)

impressive landscapes of widely but regularly spaced trees (Fig. 6.45). But the resemblance ends there. Today, the understory of diverse shrubs and grasses has been lost, perhaps in part due to increased aridity, but certainly due to rampant overgrazing (see Chap. 5). Regeneration of the native trees is negligible; substantial areas have been converted to farms and others increasingly replaced by major roads, residential development and other infrastructure; peripheral areas subject to human disturbance have been aggressively colonized by the invasive mesquite tree *Prosopis juliflora*. Air pollution from massive limestone quarrying to the north and south of Ras Al Khaimah city has undoubtedly also impacted the natural environment.

Further south, on the west flank of the Hajar Mountains from Al Ghayl south to Madam, tree cover on the gravel plains (dominated by *A. tortilis* but with occasional Ghaf *Prosopis cineraria* and Sidr *Ziziphus spina-cristi*) has been less dense throughout the modern era, but all the same influences set out above have combined to create a severely degraded environment, impoverished in both abundance and diversity of vegetation. Inspection along roadside fencing in plains areas, e.g. along E102 east of Mleiha, reveals that even the modest ground cover of annual seedlings that sprouts after light rain is often missing on the grazed side of the fence.

In that same area, however, the gravel plains are occasionally home to healthy stands of *Rhazya stricta* (Apocynaceae), a dwarf shrub toxic to quadrupeds that is a sure indicator of overgrazing (Fig. 6.46). *R. stricta* is, however, a favored source of nectar for the Painted Lady butterfly *Vanessa cardui*, and it flowers early in the year, paradoxically making some areas of the otherwise degraded plains a magnet for many thousands of these butterflies on their annual migration northward to cooler climates (Feulner et al. 2021). The bristly *Heliotropium kotschyi* (Boraginaceae) is another unpalatable plant popular with multiple butterflies because it is a particularly

Fig. 6.45 *Acacia tortilis* dominates the alluvial plains on the northwest flank of the mountains, to the east and south of Ras Al Khaimah city, but today there is little or no understory and no regeneration of the trees themselves, due to overgrazing. Scientists at New York University—Abu Dhabi have determined that the average orientation of the trees on plains like these in the UAE is not vertical. Instead they are oriented 187°, nearly due south, and tilted at a 25° angle, approximating the overhead position of the midday sun at this latitude, averaged for the year (Ross and Burt 2015). South is roughly to the left in this photo, which appears to support that conclusion. Photo credit: Gary Feulner

rich source of bio-active chemicals (Feulner et al. 2021); it often colonizes waste ground around farms or other human installations on the gravel plains.

Several UAE reptiles have their principal habitats on the gravel plains. Despite the depredations described above, the diurnal lizard *Mesalina adramitana* and the nocturnal gecko *Bunopus tuberculatus* remain reasonably common, but populations of two Fringe-Toed Lizards (*Acanthodactylus* spp.) appear likely to have suffered. The only recently recorded populations of *A. boskianus* (see Fig. 6.14b, above) are from wadi environments within the western mountain front, and most of the known UAE range of *A. opheodurus*, being on the plains north of Jebel Hafeet, has been given over to residential development.

On the East Coast, where the alluvial plain is equivalent to the coastal plain, the situation is similar, except that invasion by *Prosopis juliflora* has been more pervasive and, the available land area being smaller, the extent of its sacrifice to development has been proportionately greater.

Fig. 6.46 The unpalatable shrub *Rhazya stricta* dominates many areas of the alluvial plains west of the mountains, especially in the south, between Dhaid and Madam—a sure indication of overgrazing. Photo credit: Gary Feulner

6.3 Axes of Transition: Ecosystem Gradients in Space and Time

6.3.1 Spatial Gradients: Latitude, Climate, Behavior, Biogeography

The UAE/Oman Mountains straddle the Tropic of Cancer, spanning the conceptual and practical gradient from tropical climate in the south to subtropical or temperate in the north. The mountains also span the northerly extent of the Indian Ocean Southwest Monsoon (IOSM), which brings relatively abundant summer rainfall to the south, particularly in the Jebel Akhdar range. The Hajar Mountains of the UAE are the lowest area of the UAE/Oman mountain chain, so the orographic rainfall effect of the mountains themselves is reduced there. These geographical and climatic gradients result in significant physical and biotic changes as one moves northward from northern Oman into the UAE, and the changes manifest a directional character beyond any variation that might be expected from 'mere' speciation in a relatively rich and variegated environment.

A number of common plant and animal species disappear northwards from northern Oman into the UAE. It is often difficult to identify or disentangle the precise variables that control the distribution of a species, and not all species

Fig. 6.47 *Tamarix aphylla* trees (Tamaricaceae) can grow to large size. They grace the lower and middle reaches of many wadis on the interior flank of the mountains in northern Oman, as seen here in Wadi Ajran. But north of Wadi Jizzi, only a few scattered trees are known. Photo credit: Gary Feulner

disappear at exactly the same latitude, but a rough boundary can usefully be designated at 24° 15' North (Feulner 2011, 2016), approximating the latitudes of Wadi Jizzi, Al Ain and Buraimi. Examples of some of the more common and prominent mountain plants that disappear at or near this horizon are several large shrubs/small trees: *Acridocarpus orientalis* (Malpighiaceae), the larval foodplant of the Giant Skipper butterfly *Pyrrhiades anchises* (see Fig. 6.44); *Maerua crassifolia* (Capparaceae), a favorite of several Pierid butterflies; and *Tamarix aphylla* (Tamaricaceae), often a very large and abundant species of gravel wadi beds to the south (Fig. 6.47). Other plant species begin to disappear northward at about the same horizon, but more gradually, e.g., *Schweinfurthia papilionacea* (Scrophulariaceae) and *Cleome scaposa* (Capparaceae).

Animals that disappear north of the Al Ain/Buraimi area include *Pristuris carteri*, a semaphore gecko found primarily in Dhofar but which extends into northern Oman, especially along the mountains and foothills on the interior (southwest) flank, as well as three butterfly species: the Desert Orange Tip *Colotes liagore*, the Yellow Pansy *Junonia cebrene* and the Giant Skipper *Pyrrhiades anchises* (Feulner et al. 2021). The butterflies, however, may be responding primarily to the disappearance of their respective host plants rather than to climatic factors directly; that is certainly true for *C. liagore* and *P. anchises*. The Fig Blue butterfly *Myrina silenus*, an Afrotropical species, also tapers out gradually from northern Oman through the mountains of the UAE to the Dibba Zone (Feulner et al. 2021; Kh. Rafeek, unpublished data) although its larval host plant, the Wadi Fig *Ficus salicifolia* (Moraceae), remains common throughout the Ru'us Al Jibal to the north.

The UAE also projects into the Palearctic region. Moving north, Palearctic species of plants and animals are encountered more frequently, especially at higher elevations. The role of the high Ru′us Al Jibal in particular, as a distinct biome hosting many Irano-Turanian plant species and relict Palearctic fauna, has been discussed above. The proximity of the Palearctic boundary is also evidenced by floral and faunal records from Abu Dhabi's offshore islands. Although they are not very far north of the mainland, those islands account for most of the UAE records of Palearctic species such as *Mesymbryanthemum nodiflorum* (Aizoaceae) (Jongbloed et al. 2003), common on the coasts of Qatar, and *Pieris rapae* (Pieridae), a very common butterfly of temperate Europe and West Asia, but very rare on the UAE mainland (Feulner et al. 2021).

Latitude may influence not only the plant and animal species that are present, but also their behavior. For example, animals that hibernate or are inactive in winter in Northern Arabia do not necessarily hibernate in the UAE. Examples include Bosc's Fringed-Toed Lizard *Acanthodactylus boskianus* (Roobas and Feulner 2013) and butterflies such as the Desert White *Pontia glauconome* (Feulner et al. 2021).

An Oman-Makran distribution is a recognized biogeographical phenomenon (Kürschner 1986; Léonard 1989; Feulner 2011). Examples include the common Mountain Spurge *Euphorbia larica* (Euphorbiaceae) (although an isolated occurrence is recorded from Yemen; G.M. Brown, pers. comm.) and the plant genera *Pteropyrum*, *Phagnalon* and *Schweinfurthia* (Zohary 1963, 1973). However, a number of relatively common Oman-Makran species are absent from the northernmost UAE mountains. Examples include the Dwarf Palm *Nannorrhops ritchieana* (Arecaceae), the Wild Olive *Olea europaea* (Oleaceae) and the tropical Afro-Indian butterflies *Colotis danae* (Scarlet Tip), and *Colotis liagore* (Desert Orange Tip) (Feulner et al. 2021). This emphasizes the geographical and climatic distinctiveness of the northern mountains.

Somewhat more surprisingly, at least a few familiar plant species, when scrutinized more closely, appear to display unexpected and so far unexplained anomalies in distribution between the east and west flanks of the Hajar Mountains in the UAE. For example, the often abundant west flank annuals *Erucaria hispanica* (Brassicaceae) and *Sclerocephalus arabicus* (Caryophyllaceae) were not recorded in the drainage areas of Hajar Mountain wadis debouching to the East Coast during the period of a two-year survey there (Feulner 2016). The same is true of the perennial bulrush *Juncus socotranus* (Juncaceae), although the latter is common in a "wet" wadi draining from the southern edge of the Ru′us Al Jibal into Wadi Fay in the eastern half of the Dibba Zone.

6.3.2 Temporal Gradients: Winners and Losers from Human Activities

The pace of human activity adds a temporal element to ecosystem change in the UAE, beyond the recognized phenomenon of global climate change. Landscapes can be changed and habitats created or obliterated, seemingly overnight.

Human activities are seldom neutral from the point of view of natural environments and the ecosystems they host, but neither are they uniformly negative (see Chap. 23). The most common problem is that they disturb the natural dynamic equilibrium of local ecosystems in ways which too often work in favor of a small number of native or (more often) introduced species at the expense of many other species.

As just one example, over the past 25 years the construction of dams has proliferated in UAE mountain environments and has come to include most mountain wadis (Fig. 6.48). The advantages and disadvantages of dams at various scales and for various purposes have been the subject of debate internationally for decades. In the UAE, birdwatchers often consider dams a positive contribution, facilitating the passage of migrants and incidentally concentrating the birds for easy viewing. Naturalists more concerned about preserving existing wadi habitats and native species, or about groundwater levels in downstream areas and the alluvial plains beyond, generally have a different view.

A recent survey provides a snapshot of the diverse plant species found at more than 60 mountain region dams and water breakers (Mahmoud et al. 2018). These settings are "seed traps" for all the seeds that flow downstream during a rain, and evidently the fine, damp, clay-rich sediment deposited behind dams after periodic flooding creates good habitat for at least the initial propagation of many species, including both locally rare and exotic ones.

Historical experience allows us to add context to many names on the "dams" list. Some examples include the following: (i) The prickly amaranth *Amaranthus albus* (Amaranthaceae), first noticed in late 1999 in a newly plowed field in Wadi Maydaq (Jongbloed et al. 2003), is now common and conspicuous in silt at many dams and

Fig. 6.48 In recent decades, dams and sumps have been created in mountain areas on many scales: (**a**) Wadi Wurayah dam, successor to an earlier 1980s incarnation. (**b**) A bulldozed sump below Kadra dam in Wadi Asfani. (**c**) A shallow temporary pond in Wadi Hala, created by a graded road crossing. Photo credits: Gary Feulner

Fig. 6.49 Some plant species that have been expanding their UAE presence, facilitated by dams and sumps: (**a**) A large stand of *Amaranthus albus*, thriving at a sump beside a major pipeline route. (**b**) *Tephrosia nubica* has been expanding northwards for more than a decade, exploiting silt deposited behind dams and at other places where normal wadi drainage has been impeded. Possibly its spread has been facilitated by global warming. The tall, inverted conical shape of the plant is characteristic and helps to distinguish it from the much more common *T. apollinea*. (**c**) A stand of *Cyperus rotundus* (foreground) beside the Qashash Dam near Kadra. Photo credits: Gary Feulner

sumps in mountain wadis (Fig. 6.49a). (ii) *Tephrosia nubica* (Fabaceae) is very similar to the much more common *T. apollinea* in gross appearance, but is taller and thinner, with fuzzy, sub-ovate fruits (Fig. 6.49b). Once largely restricted to the mountains south of the Hatta Road, in the past decade or so this species has been expanding its range northward into the UAE, particularly where dam-induced flooding has deposited silt (Feulner pers. obs., N. Asmita pers. comm.). (iii) *Cyperus rotundus* (Cyperaceae) (Fig. 6.49c) is an aquatic sedge that favors damp, silty pond margins. Once limited to a few sites with year-round surface water, it is now locally common in silt behind several dams along the western mountain front. (iv) The carpetweed *Glinus lotoides*, a regional species, was first recorded in the UAE in 2016 (Mahmoud et al. 2018); it is now a dominant species behind many dams, where it boosts the populations of a few local butterflies and moths that can exploit it.

Apart from dams, the hand of man can sometimes turn rare endemics into locally more pedestrian species. Two uncommon UAE/Oman endemics—the gangly annual daisy *Launaea omanensis* (Asteraceae) (Fig. 6.50a) (N. Asmita, pers. comm.) and the prostrate *Schweinfurthia imbricata* (Scrophulariaceae) (Fig. 6.50b)—have been shown to be effective colonizers of ground disturbed by bulldozing and grading along roads and tracks. Even the much more common endemic *Pteropyrum scoparium* (Polygonaceae) is seen to prosper along the low gravel berms beside graded wadi tracks in harzburgite terrane.

It is instructive to attempt to monitor such phenomena, because they teach us how our various ecosystems respond to change. It is also potentially important, because it allows us to recognize and intervene in the event of genuinely undesirable or threatening outcomes. But in reporting results such as these, it is essential that the non-professional public should not be misled to think that the discovery of new species or the proliferation of rare species under such conditions is in any way a positive contribution to genuine biodiversity or to ecosystem health, or that they represent anything other than a disruption of the long-term natural order, with consequences that should be suspect in the first instance.

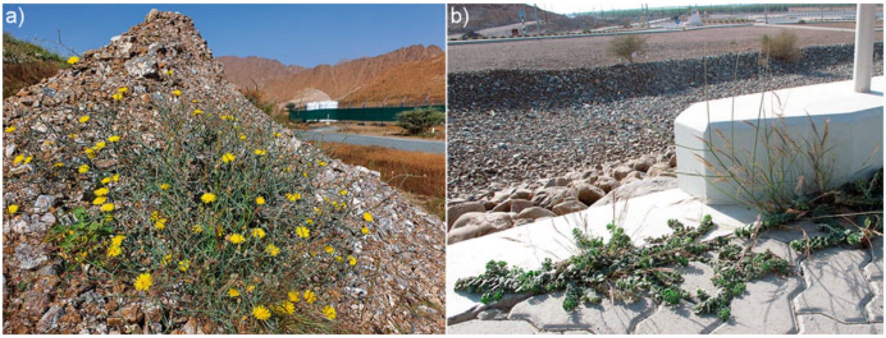

Fig. 6.50 Rare UAE/Oman endemic plants in prosaic anthropogenic locations: (**a**) *Launaea omanensis* along a bulldozed berm in Wadi Wurayah National Park. (**b**) *Schweinfurthia imbricata* among decorative paving stones on a promenade at Siji Dam. Photo credits: Nuri Asmita (a); Gary Feulner (b)

6.4 Conclusions

The mountain regions of the UAE constitute a complex biogeographical unit featuring a distinctive flora and fauna and a multitude of interrelated ecosystems. They remain, however, *terra incognita* to most biological researchers and to the general public, primarily due to limited vehicular access and the arduous and potentially dangerous nature of extended expeditions on foot. The results of the author's explorations and investigations over more than three decades are presented here in order to put that information more securely in the public record. The effort has been made to highlight items that might provoke further inquiry.

The author has been privileged to enjoy residence in the UAE during a time when his activities were welcomed and encouraged, and joins in congratulating the country on more than 50 prosperous years of federation. Regrettably, the world has moved on in some respects. In an era of heightened security concerns, the perceived need for increased regulation of individual initiatives, and the commoditization of human interactions with the natural environment, it would be much more difficult for current researchers to undertake efforts of similar scope. That makes it all the more important to give the foregoing account.

6.5 Recommended Reading

Flora of the Ru'us Al Jibal (Feulner 2011) and *Flora of Wadi Wurayah National Park* (Feulner 2016) are copiously illustrated accounts of those two fundamental but contrasting UAE mountain environments (the carbonate sediments of the Musandam versus the ultrabasic ophiolite of the Hajar Mountains) including geographical, geological, climate, ecological and historical information and regional comparisons, as well as annotated lists of the plant species recorded.

Jongbloed et al. (2003) remains the most comprehensive, authoritative and well illustrated account of the flora of the UAE generally. Its precursor, Western (1989), contains valuable introductory descriptions of the country's different plant environments and associations, especially for coastal areas that have been lost to development in the intervening years.

Feulner (2014) introduces the Olive Highlands, an elevated 'island' of biodiversity within the gabbro terrane of the Hajar Mountains, again with many illustrations. Brown and Sakkir (2004) present the distinctive environment of Jebel Hafeet from a botanical perspective.

Feulner (2006) reviews and discusses basic precipitation data for the UAE over the preceding few decades. Parker (2009) presents a very readable summary account of the climatic history of the UAE and northern Oman over the past 350,000 years, as inferred from the geological record.

The map of wadi fish distribution in Feulner (1998), although not fully comprehensive, has often been used as a surrogate for a census of the UAE and northernmost Oman wadis that sustain permanent surface water.

Almost all of the foregoing references are now available online.

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