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ヨルダンは，国土の 90 パーセント以上が年間降雨量 200 ミリ以下という乾燥地である．なかでも，リーシャのあるシリア沙漠は，降雨量がきわめて少ない．イルビドやクフル・ユーバーのある北部の高原地帯は，この国でもっとも雨量の多い地域となっているが，それでも雨が降るのは冬季だけだ．年間の降雨量も，多くて 500〜600 ミリ程度である．そのため，国全体が慢性的な水不足で，水源の確保がかつての敵国イスラエルとの係争点の 1 つであった．

乾燥地ヨルダンの墓地は，緑が少ないということもあって，どれも殺伐とした印象を与える．とくにムスリムの墓地はそうである．来世を信じるムスリムは，墓をたんなる死者の肉体の一時的な置場としかみなしておらず，あまり関心を払わない．そのため，年月がたつにつれて墓は風化し，瓦礫と化してしまうからである．

（写真 1〜4: 清水芳見，Photos 1–4: Yoshimi Shimizu）

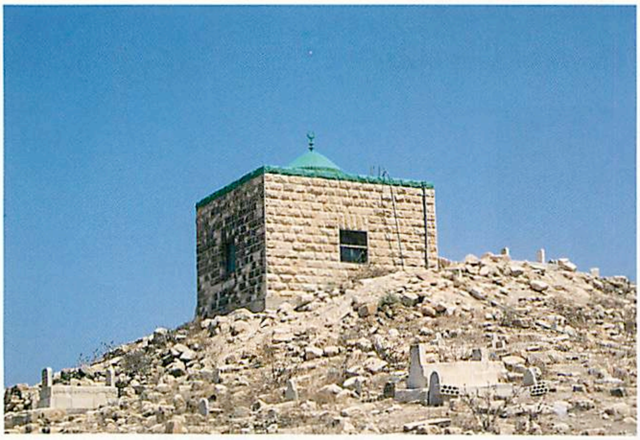

写真4. サハーバ（預言者ムハンマドの教友）の廟（ヨルダン，ソーム村）．まわりにあるのは，一般の人たちの墓．

Photo 4. The shrine of one of al-Ṣaḥāba (the Companions of the Prophet Muḥammad), surrounded by the graves of ordinary Muslims (Saum, Jordan).

ムスリム聖者の廟 Tombs of Muslim Saints

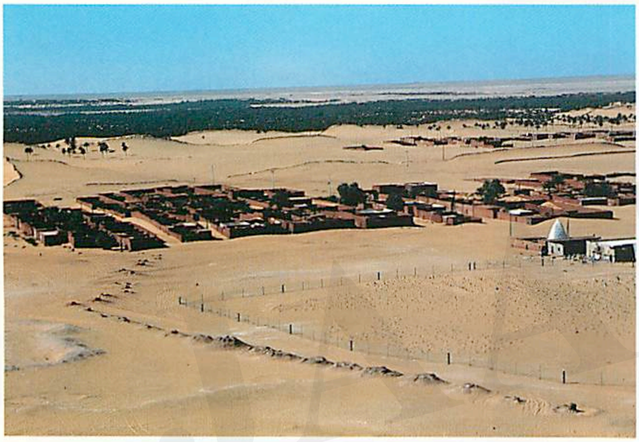

写真5. サハラのオアシス(Aoulef)と聖者廟．手前に一列に伸びるのはフォガラで，このフォガラが真ん中の集落と奥のナツメヤシ畑を潤している．聖者廟とフォガラの間は一般人の墓．これはいたって簡素．

Photo 5. A Sahara oasis (Aoulef) with a white tomb (marabut) of a Muslim saint standing up near a foggara, vital line for the village and the dates fields.

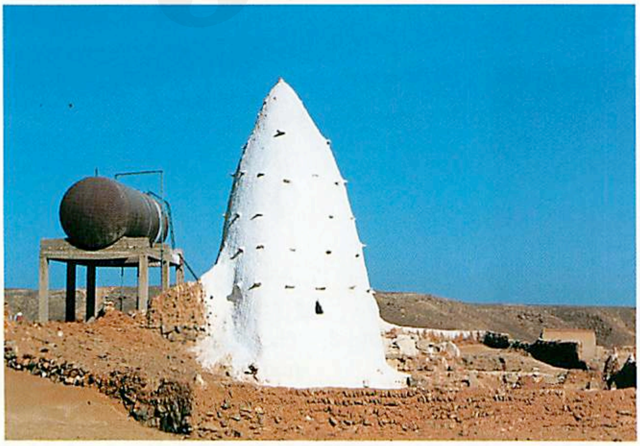

写真6. 給水塔が故意か偶然か，横に据えられていたサハラ・オアシス（In Belbel）の聖者廟．聖者廟の周囲にはやはり簡素な一般人の墓がある．

Photo 6. A white tomb (marabut) of a Muslim saint and a water tank instaaled near it at a Sahara oasis (In Belbel).

沙漠地帯の死生観をめぐる最大の謎は，ピラミッドをつくった古代エジプトのように丁重な死者儀礼をおこなう社会が存在した一方で，その後のイスラーム文化は，死者儀礼の徹底的な簡素化をおこなったことであろう．しかしフォガラで知られるサハラのオアシス地帯では，聖者崇拝が盛んで，各オアシスには必ず白く塗られた巨大な聖者廟が屹立していた．いわれを尋ねてみると，フォガラの開削などと関係しているらしい．沙漠地帯の生活様式は，灌漑による徹底した集約農業がおこなわれるオアシスと，疎放な遊牧がかろうじてできるだけの荒野との間に強烈なコントラストがある．死生観，死者儀礼のコントラストもこれにどこかで対応しているのではないだろうか．

（写真5･6：嶋田義仁，Photos 5, 6: Yoshihito Shimada）

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アラブ・ムスリム社会の墓制―ヨルダンの事例―

清 水 芳 見*

1. 序

イスラームの終末思想では，終末の日は，何の前ぶれもなく，突然の天変地異という形で訪れるとされている．このとき，復活によって死者の霊魂と肉体は生前と同じ姿に戻され，蘇った人間たちはすべてアッラーの前に引き出されて，最後の審判を受けなければならない．この審判によって，天国に入れられた信仰者は，永遠に平安な生活を送ることができるが，地獄に入れられた不信仰者は，煮えたぎる熱湯を飲まされ，業火に焼きつくされる．

このような考え方は，ムスリムの死体の処理方法にも反映されている．都市部に住んでいるか，村落部に住んでいるか，あるいは沙漠で遊牧生活を送っているかというようなことには関係なく，ムスリムはみな死体をかならず土葬にし，けっして火葬にはしない．これは，火でもって人間を焼くことは，アッラーだけが与えることのできる罰だとされているからである．また，ムスリムのなかには，この土葬の慣習について，肉体を焼いて灰にしてしまったら，最後の審判のときに，霊魂の戻るところがなくなり，蘇ることができなくなるからだという者もある．

以上のように，ムスリム社会では土葬の慣習が行なわれているが，こういった慣習をふくめ，この社会の死の問題についての人類的な研究は，これまでじゅうぶんになされていないのが現状である．

筆者が主な研究対象としてきたアラブ・ムスリム社会について見ると，民族誌のなかで，死をめぐる慣行に関してしばしば記述がなされている（たとえば，KATAKURA, 1997: 95–97（サウディアラビア）；CARTER, 1982: 108（オマーン）；FERNEA, 1969 (1965): 289–293（イラク）；SWEET, 1974 (1960): 213–215（シリア）；LUTFIYYA, 1966: 62–67（パレスチナ）；FAKHOURI, 1972: 87–90（下エジプト）；BLACKMAN, 1968 (1927): 109–128（上エジプト）；IBRAHIM, 1979: 122–124（スーダン）；WESTERMARCK, 1968 (1926): 434–560（モロッコ））．また，当時ヨルダン領であったヨルダン川西岸地区にあるパレスチナ人の村を調査した Hilma GRANQVIST は，とくにこの村のムスリムの死をめぐる慣行に関する著書を残しているが〔GRANQVIST, 1965〕，これは，アラブ・ムスリムの死の問題のみを取り上げた著書としては唯一のものである．

ただ，内容を見ると，上記の民族誌のなかの記述でも，GRANQVIST の著書でも，死をめぐる慣行についての分析はほとんどなされておらず，たんに事例が提示されているにすぎない．つまり，アラブ・ムスリム社会に関していうと，死をめぐる慣行についての報告はしばしばなされているが，まとまったものは少なく，しかも，どれも記述主体で人類学的な分析をともなったものはほとんど見られないのである．

アラブ・ムスリム社会でなく，パキスタンで起きたシーア派ムスリムの入水事件をもとにムスリムの死生観等の問題を論じた Akbar AHMED は，その論文の序で，「こういった問題を扱った人類学的な文献はあまり多くないが，…（中略）…なかでもムスリム社会に関する資料は乏しい」と述べているが（AHMED, 1986: 120），アラブ・ムスリム社会について見た場合，上記のように，AHMED の指摘はいっそう的を得ている．

筆者は 1986 年 1 月から 1988 年 4 月まで，社会人類学調査を行なう目的で，ヨルダン・ハーシム王国（以下，たんにヨルダンという）のヤルムーク大学付属考古学・人類学研究所に留学し，主として同国北部のイルビド県にあるクフル・ユーバー (Kufr Yūbā) というアラブ・ムスリムの農村で，調査に従事した．この村では，1986 年 4 月から 1988 年 4 月まで，墓制をふくめ総合的な社会人類学調査を行ない，また，1992 年の 7 月から 8 月にかけて，再度調査を行なった．

第 1 回の調査の折には，東部のシリア沙漠のなかにあるリーシャ (al-Rīsha) というベドウィンのセトゥルメントでも，短期ではあったが，遊牧ベドウィンのなかのルワラ族 (Rwala) の調査を行ない，墓制に関しても資料を得ることができた．彼らも，全員がアラブ・ムスリムである．また，2 度目の調査のときには，農村クフル・ユーバーやベドウィンのセトゥルメント，リーシャの墓制との比較のために，ヨルダンの諸都市のなかで 3 番目に人口の多いイルビド市 ('Irbid) において，墓制の調査を行なった．

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（受付：1994 年 7 月 25 日，受理：1994 年 12 月 8 日）

ムスリム社会の墓は一般に簡素であり，墓標さえ見られない地域もあるが，これはムスリムが上述のような終末思想をもっていることと関係している．だが，一般に簡素であるとはいうものの，墓制に関しては，地域によって違いが認められる．本稿の主たる目的は，こうしたムスリム社会の墓制がいかなる死生観あるいは社会状況に基づくものかを考察することにある．

その意味で，本稿は試行の域を出ないが，上記のヨルダンの3調査地におけるアラブ・ムスリムの墓制について，可能なかぎりこれらの地域の土葬の具体的な方法にふれながら，人類学的考察を試みてみたい．まず，3調査地の墓制[1)]について報告したのち，その報告に主として基づきながら，墓制と死生観の関係について考察を加える[2)]．

2. 定住社会の墓制と遊牧社会の墓制

本章では，定住社会の事例として，農村社会クフル・ユーバー[3)]と都市社会イルビドを，遊牧社会の事例として，ベドウィンのセトゥルメントであるリーシャを取り上げ，それぞれの墓制について報告する．

1) 農村社会クフル・ユーバーの事例

(1) クフル・ユーバーの概況

クフル・ユーバーは，イルビド市から西に6キロほど行ったところに位置する（図1）．本来は小麦栽培を主とする農村（qarya）であったが，農業従事者は減少の一途をたどり，現在では全人口の約20パーセントを占めるにすぎなくなっている．ただ，家族成員のだれかが農業に従事しているような例はまだ多く，また，農業従事者がいなくても，農地をもち，それを他人に貸して耕作させている家族もある．耕地面積についても，村の全面積に占める割合はいぜんとして高い．

この村の人口は，最初の調査時（1986–1988）では約9,000人とのことであったが，その後，1990年から1991年にかけての，いわゆる湾岸危機とそれにともなう湾岸戦争によるクウェートなどからのヨルダンへの大量の難民流入の影響を受けて，2度目の調査時（1992）には，10,000人を超えていた．そのため，この村には，最初の調査時に，約25のアシーラ（'ashīra．一族）に属するヨルダン人と，500人ほどのパレスチナ人，そして，若干名の外国人が居住していたが，2度目の調査時には，その構成も多少変わっていた．

(2) クフル・ユーバーの墓地について

現在クフル・ユーバーには，2つの墓地がある．ところが，墓地内の埋葬するスペースが少なくなってきたため，3番目の墓地をつくることが検討されている．

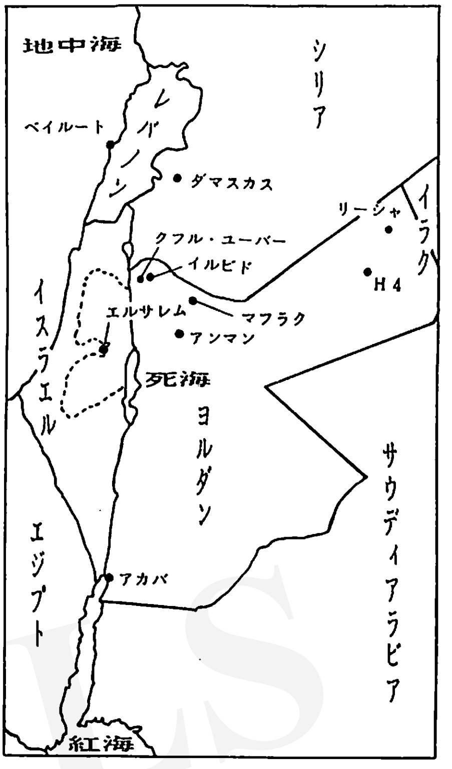

図1．調査地と周辺の諸都市．
点線で示したところは占領地のヨルダン川西岸地区．

この村では，死者の埋葬場所は，家族やアシーラごとに区画が決まっているというようなことはなく，墓地のなかの空いているところならどこでもよいとされている．そのため，どちらの墓地も，後述するイルビド市の墓地にくらべると，雑然と墓がならんでいるとの印象を与える．

(3) 墓について

ふつう日本語で「墓」と訳されるアラビア語のqabrは，「墓地」を意味するmaqbaraと同様，「埋める」という意味の動詞qabaraに由来する言葉である．一般にクフル・ユーバーでは，qabrといった場合，より具体的には，死体を埋葬した墓穴の部分とその上に置かれた墓標等を総称的にさす．

この村の墓地の墓は，その大部分がコンクリート・ブロックやセメントでできた簡素なものであるが，最近はよい材質の石を使った立派なものも目につくようになってきた[4)]（図2）．墓の色は灰色がほとんどであるが，これは墓の多くがコンクリート・ブロックやセメントでできているからである．ただ，筆者の最初の調査のあいだに，緑色の墓が1つつくられた．緑色の墓はイルビト市

図2. 比較的新しい墓の多いクフル・ユーバーの第2墓地（1986年撮影）.
手前に見えるブロックをならべただけのものが一般的な墓.

図3. クフル・ユーバーの第2墓地（1992年撮影）.
文字の刻まれた墓が墓全体に占める割合が，最初の調査時よりも高くなっている.

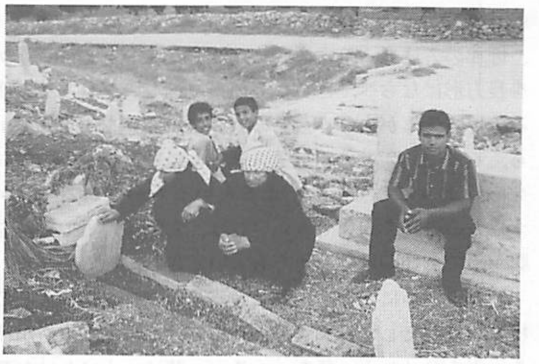

図4. イード・アル・アドハーのときの墓参で，身内の墓の前で嘆き悲しむ女たち.（1986年クフル・ユーバーの第2墓地にて撮影）

図5. できたばかりの墓を囲んで，死者のために全員でアッラーにドゥアー（祈念）を行なう.（1988年クフル・ユーバーの第2墓地にて撮影）

の墓地でも見られたが，このように墓が緑色に塗られているのは，この色がイスラームで好ましいとされているからであると考えられる.

文字が刻まれた墓碑を有する墓は，近年になって見られるようになってきたもので，墓全体に占める割合は，最初の調査時よりも2度目の調査時のほうが高かった（図3）．墓碑に刻むのは，死者の名前，死んだ日，クルアーンの開扉の章（al-Fātiḥa）などである．なかには，文字を刻まずに，ただペンキやマジックで書いただけの墓碑もある.

(4) 埋葬方法について

次に，上記のような墓ができるまでの過程を，死者が出た時点から順を追って記述してみたい（図4, 5）.

クフル・ユーバーには，ドライアイスや薬を使って死体を保存するというような習慣はないので，ここでは，死者が出ると，できるだけ早いうちに埋葬を行なう[5]．埋葬に先だって，まず日本の湯灌にあたるもの（g͟hasl al-mayyit）を行なってから，死体を kafn と呼ばれる1枚の布で巻く．kafn の色はふつう白であるが，緑色の kafn が用いられた例もあった．理由は，上述の緑色の墓の場合と同様，この色がイスラームで好ましいとされているからだと思われる.

そして，1日5回の礼拝の時刻に合わせてモスクに行き，そこで ṣalāt al-jināza と呼ばれる葬送の礼拝を行なってから，墓地で埋葬となる．墓穴は，深さが1〜1.5メートルのもので，葬列が到着するまでに掘られているのがふつうである.

死体を運ぶ棺は，死装束と同様 kafn と呼ばれることが多いが，tābūt あるいは naʻs͟h と呼ばれることもある．各モスクに1つずつ備えつけられているので，その1つを借りてきて使う．村の最古のモスクにあるものは，全体がイスラームで好ましいとされる緑色に塗られている．このように，この村の棺は，日本の棺桶とは違って，いわば担架のようなものであるから，埋葬は

kafn に巻いた死体のみを行なう.

埋葬の方法は，墓穴の底に，コンクリート・ブロックを長方形にならべ，さらにその上にべつのブロックを積み上げて死体が入るくらいの大きさの囲いをつくってから，そこに，死者の顔がイスラームの聖地マッカの方向を向くようにして，横たえるというものである．顔がマッカの方向を向いてさえいれば，右脇腹が下でも左脇腹が下でも仰向けでも何でもよいとされている.

囲いのなかに死体を入れたら，そこにコンクリートの板を数枚わたして蓋をするようにし，その上に土をかける．土をかけたら，墓をつくるが，墓は，土にかけた墓穴の部分にコンクリート・ブロックなどを長方形にならべ，その上に nāṣib と呼ばれる２枚の石板を両端（死者の頭の部分と足先の部分）に立てるというのが基本的なものである．なお，墓はすべて個人墓で，１つの墓に複数の家族成員を埋葬する，いわゆる家族墓のようなものは存在せず，また１つの墓に２人以上をいっしょに埋葬する習慣もない.

「立てる」という意味の動詞 naṣaba に由来する nāṣib は，文字が刻まれて墓碑となることもあるが，この石板を立てる本来の目的は，ここからここまで人が埋められているということを示すことにある．つまり，上記のように，埋葬場所は墓地のなかの空いているところならどこでもよいということになっているので，これを立てないと，死体が埋葬されていることに気づかずに，だれかがべつの死体を埋めようとするかもしれないからというのが人々の説明である.

2) 都市社会のイルビドの事例

(1) イルビドの概況

イルビド県の県庁所在地であるイルビド市は，ヨルダン北部最大の都市 (madīna) であり，また，1976 年創立のヤルムーク大学と 1987 年創立のヨルダン科学技術大学を抱える学園都市でもある.

1992 年１月現在の人口は，推定で約 28 万人で（The Ministry of Information, 1992)，宗教的には，ムスリムだけでなく，キリスト教徒も居住している．1961 年の統計で，全人口に占めるムスリムの割合は約 94 パーセントとなっているが（Muḥāfaẓa wa Baṭyna, 1973: 48)，出生率から考えて，現在その割合はさらに高くなっているものと推測される.

なお，本稿で以下，たんに「イルビド」といった場合は，イルビド県ではなくイルビド市のことをさすものとする.

(2) イルビドの墓地について

２度目の調査の時点で，イルビドには５つの墓地があったが，そのうちの２つが同市本来の墓地で，他の３つは，かつて独立した村で，現在行政的に一地区としてイルビドに組み込まれているバーリハ (al-Bāriḥa) にある．筆者が訪れたのは，その同市本来の墓地のうちの１つで，町の中心部の Tall ʼIrbid と呼ばれる高台に位置し，パレスチナ人の難民キャンプ[6]に隣接した墓地である．ここは同市最古の墓地で，ムスリムの区画とキリスト教徒の区画から成る.

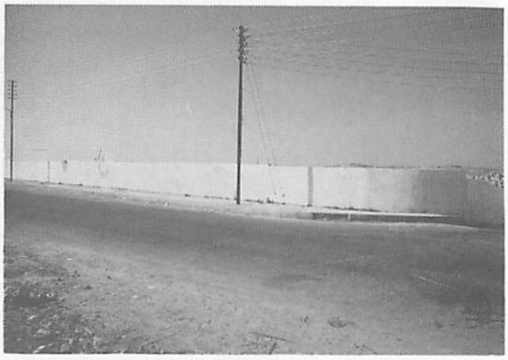

図 6．塀に囲まれたイルビド最古のムスリムの墓地.

図 7．イルビド最古のムスリムの墓地内の鉄柵で囲まれた墓群.

墓地は白い塀で囲まれ（図 6)，ムスリムの区画とキリスト教徒の区画は，難民キャンプへ通ずる細い通りで区切られている．ムスリムの区画は２つあり，総面積もキリスト教徒の区画よりはるかに広いが，これはイルビドの総人口に占めるムスリムの割合からすれば，むしろ当然のことであろう．キリスト教徒の区画に十字架を記した扉があるのに対して[7]，ムスリムの区画には，扉はないが，番人がおり，なかで子どもが遊んだり，なかに動物が入り込んだりして，墓を荒らさないように見張っている．この老番人は，住み込みではなく通いであり，ヨルダンのワクフ・イスラーム問題省から月 70 ディーナール（約 13,000 円）の給料をもらっている．勤務時間は，午前８時から午後６時までとのことであった.

この墓地のムスリムの区画には，墓が隙間もないほどぎっしりと，また整然とならんでいる（図7）．この点は，空いているところならどこに死体を埋葬してもよいとされ，雑然と墓がならぶクフル・ユーバーの墓地とはまったく趣を異にするが，都市が人口の密集地帯であることを考えると，このように隙間なく墓をならべざるをえないのであろう．つまり，こうした墓のならび方の相違は，ヨルダンの場合，村落と都市との人口数の違いに主として起因すると考えられるのである．このイルビドの墓地には，もはや新たに墓をつくる余地はないように思われたが，実際，このように過密状態になったために，他の地区に新たに墓地がつくられている．

(3) 墓について

個々の墓について見ると，やはりムスリムの墓はすべて個人墓で，家族墓のようなものはない．そういう意味では，基本的にクフル・ユーバーの墓と同じであるが，1つの鉄柵に囲まれた墓群がいくつか見られる点が，クフル・ユーバーの場合とは異なっている．そういった墓群のなかには，同一のアシーラ名が刻まれた墓碑を有するものが見られ，このことから，特定の家族あるいは親族の区画の存在がうかがえる．

墓の形態や色について見ると，クフル・ユーバーの墓にくらべて，変化に富んでおり，死者の名前などが刻まれた墓碑を有する墓が全体に占める割合も高い．このように，墓碑を有する墓が比較的多く見られるのは，大勢の人間が集まっている都市の墓地では，村落部の墓地にくらべて，同一墓地内に存在する墓の数もはるかに多く，名前が刻まれていないと，どれがだれの墓だかわからなくなるというのが，理由の1つであると考えられる．墓の色に関しても，目立つような色を塗ることで，多くの墓のなかから捜しやすいようにするとの配慮があるのかもしれない．もっとも，クフル・ユーバーの墓地に見られたような，コンクリート・ブロックを長方形にならべてその上に nāṣib を立てただけの墓や，こういった墓のコンクリート・ブロックで囲まれた部分にセメントを流し込んだ程度の墓も目につく．これらの墓には，墓碑は存在しない．

また，墓碑に刻まれた名前からわかることは，ここに埋葬された死者のなかに，さまざまなアシーラに属するヨルダン人のほかに，多くのパレスチナ人がいることである．これは，都市がいろいろな人たちの集合体であることをよく示している[8]．

なお，イルビドにおける死体の埋葬方法に関する具体的な資料は得ることができなかったが，ムスリムについては，クフル・ユーバーやリーシャの場合と基本的に同じであると推測される．

3) ベドウィンのセトゥルメント，リーシャの事例

(1) リーシャの概況

リーシャは，マフラク県の県庁所在地であるマフラク市からイラクの首都バグダードへ通ずる街道沿いに位置する，H4という町から北東に自動車で45分ほど入った沙漠のなかにある．このセトゥルメントは，遊牧民の定住化政策の一環として，1960年代にヨルダン政府によってつくられたもので，ルワラ族だけのセトゥルメントというわけではない．

リーシャにはヨルダン政府が建てたコンクリート製の家がたくさんあるが，ルワラ族をはじめここに居住するベドウィンたちは，定住せずにつねに移動しているため，空き家が目立つ．なかには，これらの家には住まず，テントで生活している者や，家の横にテントを張って，その両方で生活している者もある．

リーシャで筆者が聞き取り調査を行なったルワラ族は，ヨルダン，シリア，サウディアラビアを中心に，アラビア半島北部をかなり広範囲にわたって移動している．彼らの総人口は，自称で100万人，このグループを研究しているイギリスの人類学者の推定でも，その半分くらいにはなるという（清水，1989: 23)[9]．

(2) リーシャの墓地について

リーシャには，ベドウィンの墓地が3つ存在する[10]．もっとも，「墓地」といっても，農村社会クフル・ユーバーや都市社会イルビドの墓地とはまったく異なり，他と区別された特定の区画があるわけではない．セトゥルメント周辺の，同じような景観の沙漠のなかに，石を積み上げた，何かの目印のようなものがいくつか見られるところがあり，それが彼らのいう「墓地」なのである．クフル・ユーバーの墓地も，イルビドの墓地も，一見して墓地だとわかるが，このリーシャの墓地は，「墓地」だといわれなければそれとはわからない．

(3) 墓について

イスラームでは偶像崇拝につながるようなことは禁じられているため，ムスリムの墓は本来簡素なものでなくてはならないとされる．ところが実際には，そうでないものも，ところによっては見られる．たとえば，一般に「聖者」と呼ばれる人たちの墓がその典型的なものである[11]．上述のように，農村社会クフル・ユーバーの墓は概して簡素であるが，リーシャの墓地のベドウィンの墓は，それよりもはるかに簡素であった．

どの墓も，自然の石が積み上げられているだけで，加工された墓石といえるようなものはない（図8）．なかには，長年の風雨その他によって，積み上げられた石の大部分が散逸してしまっているものもある．そういった，石の大半が散逸した墓を観察したところ，そのなかの1

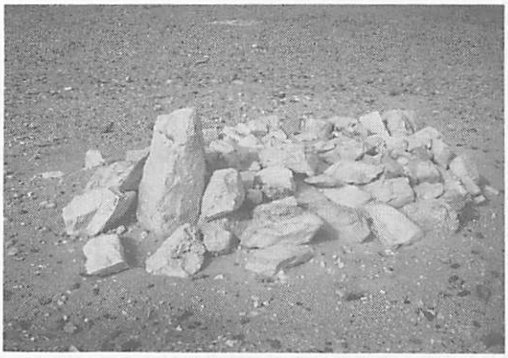

図 8. リーシャの墓地の墓.
まだ比較的新しいものと思われる.

図 9. リーシャの墓地の墓.
積まれた石の大部分が散逸しているが，残った石のなかに，「bismillāhi ar-raḥmān ar-raḥīm」と彫られたものが 1 つ見られた.

表 1. 3 調査地の墓制の比較

			都市社会の墓制（イルビド）	農村社会の墓制（クフル・ユーバー）	ベドウィンのセトゥルメントの墓制（リーシャ）
墓地	他の空間との区別	区画	○	○	×
		塀	○	×	×
	番人		○	×	×
墓	形態の簡素さ		○	○	◎
	墓碑		◎	○	×
	並び方の整然さ		○	×	×

つに，「bismillāhi ar-raḥmān ar-raḥīm（慈悲深く慈愛あまねきアッラーの御名において）」と彫られた石が残っているものがあった（図 9）. ルワラ族の風俗習慣に関する最初のまとまった報告である Alois Musil[12] の著書では，死体を埋葬したあと，石や土で墓穴を塞ぎ，その上に naṣājeb と呼ばれる石を，男の場合 2 個，女の場合 1 個置くとなっているから（Musil, 1928: 670），墓の簡素さは，Musil の調査当時も現在も，基本的に変わっていないということになろう.

(4) 埋葬方法について

ルワラ族の死体の埋葬方法は，まず死体を洗ってから，白い布（kafn）で包み，それを，右脇腹を下にし，顔をマッカの方向である南に，頭を西に向けて横たえるとのことであった. Musil の報告でも，死体は，右脇腹を下にし，顔を南に向けて埋葬するとなっている（Musil, 1928: 671）.

3. 考察—墓制と死生観の関係を中心に

前章では，クフル・ユーバー，イルビド，リーシャの 3 調査地の墓制について報告した. 本章では，それらの報告に主として基づきながら，墓制と死生観の関係を中心に考察を試みる[13]（表 1）.

1) 墓地について

本稿で取り上げた 3 調査地の墓地の外観は，図にも示されているように，かなり異なっているが，ことに定住社会と遊牧社会との相違は顕著である. ようするに，農

村社会クフル・ユーバーや都市社会イルビドの墓地は，他の空間と区別された特定の区画であることがはっきりしているのに対し，ベドウィンのセトゥルメントであるリーシャの場合，墓地と他の空間との区別が曖昧なのである．

こういった相違に関しては，定住と遊牧という生活様式の違いが一因として考えられる．つまり，墓地と他の空間との区別が必要になる頻度を，定住生活を送る農村や都市の人々と遊牧生活を送る人々とでくらべてみると，前者のほうが後者よりもその頻度が高くなる．これは，前者の場合，生活空間が固定されていて，そのなかにつねに墓地が入ってくるのに対し，後者のほうは，生活空間が動いていて，そのなかにつねに墓地が入ってくるとはかぎらないからである．

2) 墓について

墓地に存在する墓の形態は，どの調査地の場合も概して簡素である．なかでも，ベドウィンのセトゥルメントであるリーシャの墓地の墓の簡素さは顕著であるが，このような相違は，定住と遊牧という生活様式の違いに起因するとはかならずしもいえないと思われる．なぜなら，同じ遊牧民の墓でも，墓碑などが立てられているものが存在するからである．

たとえば，ネゲヴ沙漠のアブー・グウェイド族というベドウィンでは，墓に墓碑を立てることがある．確かに，このベドウィンの場合，墓碑が立てられるのは有力者の墓だけであるが（Marx, 1967: 218），こういった有力者の死に際しては，墓碑は恒常的に立てられている．この点，有力者か否かに関係なく，すべての墓が墓碑を有しないリーシャの場合とはやはり異なる．

さらに，シナイ半島のムゼーナ族というベドウィンは，自分たちの始祖とされる人物の墓に廟を建てており，彼らは一族のシンボルとなっているこの廟を定期的に参詣に訪れる（Marx, 1977: 46–47）．こういった廟をともなうく墓は，彼らの墓のなかではきわめて例外的なものであるが，それでもこういう墓がつくられているという事実は厳然として存在する．

以上の2例は，遊牧という生活様式がかならずしも簡素な墓をつくる動因にはならないということを示している．つまり，遊牧民はその生活様式ゆえに簡素な墓をつくるとは，かならずしもいえないということになる．

むしろ，リーシャの場合，墓のこういった極端な簡素さは，ここを根城にするベドウィンのなかに，ルワラ族のような，サウディアラビアにまたがって移動している一族が存在することに，一因があるのではないかと考えられる．つまり，サウディアラビアは，イスラームのなかでも，厳格で復古主義的なワッハーブ派を標榜していることから，この宗派の影響を彼らが受けている可能性があると思われるのである．

18世紀末にアラビア半島とその近隣を席巻したワッハーブ派の信徒たちは，廟や墓を徹底的に破壊したが（清水，1984: 22），この宗派の理念を基礎として1932年に建国されたサウディアラビアでは，たとえば，首都リヤドのような都市においても，墓に墓碑や墓標が立てられているような例は知られておらず，墓といえば，たんに人が埋められていることを示す石が地面に置かれている程度のものにすぎない．この点は，一般のムスリムだけでなく，国王の場合も同様である（大塚，1985: 213）．実際ルワラ族のなかに，このワッハーブ派の教義を受け入れている者があること（Lancaster, 1981: 129）を考えると，リーシャの墓の極端な簡素さの一因がこの宗派の影響によるものであることが，1つの可能性として推測される．

3) 家族墓について

1つの墓に複数の家族成員を埋葬する家族墓に関しては，ヨルダンの場合，クフル・ユーバー，イルビド，リーシャの3調査地には見られなかったものの，アラブ・ムスリム社会全体に家族墓が存在しないというわけではない．ただ，筆者が調べたかぎりでは，家族墓に関する報告があるのはエジプトだけである．しかも，エジプトのすべての墓が家族墓というわけではなく，個人墓に関する報告も見られる（たとえば，Fakhouri, 1972: 88; Blackman, 1968 (1927): 115–116; Lane, 1973 (1836): 522; 大塚，1985: 216）．

エジプトの家族墓がどういうものであるかを Hani Fakhouri の報告で見ると，彼の調査地の家族墓は，拡大家族ごとにつくられる．構造的には，男の区画と女の区画に分かれた小さな部屋から成るが，この部屋は地下につくられており，地上に出ている部分は2，3フィート程度の長さである．材質はふつう石で，上部はセメントで固められている（Fakhouri, 1972: 88）．

エジプトにおいて，個人墓と家族墓のどちらの形態が一般的であるかに関しては，たとえば，同じ下エジプトの場合でも，個人墓とする意見（Fakhouri, 1972: 88）と家族墓とする意見（大塚，1985: 216）の両方がある．墓が家族墓になるか個人墓になるかについて，Winifred S. Blackman は，墓地の土壌の性質によるとしている．つまり，低地の沙漠では個人墓になり，それ以外の，たとえば農地に連なるような場所では，家族墓になる傾向があるというのである．その理由は，沙漠地帯では，墓をあらかじめつくっておくことが難しく，死者が出るた

びごとにつくらなくてはならないからであるという(Blackman, 1968 (1927): 115).

4) 死生観をめぐって—3調査地に共通する墓の簡素さの背景にあるもの

家族墓は，アラブ・ムスリム社会のなかでもエジプトにだけ見られるもののようであるが，なぜエジプトにだけ見出されるのか，その理由は不明である．もっとも，ムスリムにとっては，墓が個人墓であるか家族墓であるかはあまり重要なことではない．なぜなら，家族墓が存在する場合でも，そこに埋葬されている人たちの，死後のその家族との絆はきわめて弱いからである．

日本では，祖先崇拝によって，家族とその墓は密接に結びついているが，ムスリム社会の場合，墓と家族[14]の結びつきはひじょうに希薄である．したがって，ムスリムのあいだには，「家族は墓を末代まで守り，維持してゆかねばならない」というような考え方は存在しない．これはムスリムの死生観の根幹に関わることであり，本節では，この点をさらに詳しく検討してみたい．

(1) 瓦礫化した墓が意味するもの

近年クフル・ユーバーの墓地では，よい材質の石を使った立派な墓がつくられるようになっているが，他方で，たんなる瓦礫となった墓も数多く見られる．ことに，最初につくられた古いほうの第1墓地[15]の墓のほとんどは，こういった瓦礫と化したものである．新しいほうの第2墓地の場合は，第1墓地に新たな墓をつくるスペースが少なくなってきたためにつくられたものであるから，そこには比較的新しい墓が多く，瓦礫となった墓は，瓦礫化が著しい第1墓地にくらべると少ない．ただ，両方の墓地に共通しているのは，その大部分がもともと簡素なものであり，しかもムスリムの場合，墓を末代まで維持してゆくという考え方がないため，年数が経って訪れる人がいなくなると[16]，風雨その他によっていずれ瓦礫と化し，どれがだれの墓だかわからなくなってしまうという点である．

この村では，最近になって，文字の刻まれた墓碑を有する墓が，第2墓地のほうに見られるようになってきたが，墓全体に占めるその割合はまだ高いとはいえない．また，前章で述べたように，こういった，墓碑を有する墓のなかに，墓碑の文字がペンキやマジックで書かれただけのものが存在する．こういう墓には，後世まで墓碑を残そうという意志を認めることができない．

クフル・ユーバーのある青年は，自分の祖父母の墓について，母方の祖母の墓は名前が刻まれているのでどれであるかわかっているが，父方の祖父と母方の祖父の墓は，名前が刻まれていないのでわからないと述べた．この青年の発言には，彼らが少し前の世代の家族の墓に対してさえ，あまり関心を払っていないということが示されている．名前が刻まれていなくても，どこにあるか彼らがわかっているのは，上の世代では，せいぜい両親の墓くらいのもので，ましてや何代も前の祖先の墓などというものは，だれも覚えていないのがふつうなのである．

祖先の墓に対するこうした関心の薄さは，ベドウィンのセトゥルメント，リーシャの場合も，都市社会イルビドの場合も，基本的に同じであると考えられる．なぜなら，リーシャの墓地の墓は自然の石を積み上げただけのきわめて簡素なものであったが，そういった墓のなかに，積まれた石の大部分が散逸して，ふつうの地面とほとんど変わらなくなっているものが数多く存在する．ひじょうにたくさんの墓が整然とならぶイルビドの墓地にも，数はクフル・ユーバーの場合ほど多くはないが，やはり瓦礫と化した墓が見られるからである[17]．

(2) 慰霊の欠如

祖先の墓に対して関心が薄く，墓が瓦礫化しやすいムスリム社会には，当然のことながら慰霊行為は存在しない．

ここでいう慰霊とは，死者が生者の生活を左右することがあるという前提のもとに，死者との関係を良好に保つために生者が行なう行為を意味する．たとえば，日本では，死者は不安定な存在であり，生者に危害を加える恐れがあるとされるが，慰霊をじゅうぶんに行なえば，安定した祖先となって子孫に幸福や繁栄をもたらしてくれるとも考えられている(渡辺，1959: 119–120)．日本人が，墓を末代まで維持していくことに固執するのはこのような祖先崇拝によるもので，死後の住処とみなされることのある墓(藤井，1993: 21; 中牧，1993: 282–284)をきちんと守っていくことで，死んだ祖先との関係を良好に保とうとするのである．

これに対して，クフル・ユーバーでは，ふつう死者が生者に対して何らかの直接的な影響力[18]を及ぼすことができるとは考えられていない．したがって，死者との関係を良好に保つために，立派な墓をつくる必要もなければ，さらにその墓を末代まで守り，維持していく必要もないということになる．なぜなら，そのようなことを行なわなかったからといって，死者が生者に祟ったり危害を加えたりすることはなく，また行なったからといって，死者が生者に幸福や繁栄をもたらすこともないからである[19]．

このように，古い墓が瓦礫化していく背景には，祖先崇拝の欠如によって特徴づけられるムスリム社会特有の死生観が存在するものと考えられる[20]．

(3) 死者崇拝の欠如

ムスリム社会に欠如しているのは，祖先崇拝だけではない．祖先にかぎらず，死者一般に対する崇拝の観念や慰霊行為が欠けている．

筆者は，クフル・ユーバーの人たちが墓や墓地についてどのように考えているか，彼らの何人かに尋ねてみたことがある．すると，「墓地は，神聖な (muqaddas) ところ[21]ではないが，敬意 (ʼiḥtirām) を払うべきところではある」という答えが一様に返ってきた．この場合の彼らがいう敬意とは，具体的には，踏むなどして墓を傷つけたり，墓標の上に腰をかけたりしないということである．

しかし，墓参のときの彼らの実際の行動を観察していると，確かに自分の訪れる墓に対しては敬意を払っていると思われるが，それ以外の墓，とくに瓦礫と化したようなものについては，踏みつけたり，墓標の上に腰をかけたりしている光景がしばしば見られた．これらのことから考えると，彼らの墓一般に対する敬意の度合いや墓地全体に対する敬意の度合いは，むしろ低いように思われる．

このような，墓や墓地に対する彼らの敬意の度合いの低さは，墓参のとき以外の，墓や墓地に対する彼らの態度にも認められる．

クフル・ユーバーの人々のなかには，墓参に際して，墓の上に花を置いたりする者があるが，彼らの説明によると，これは墓が美しく見えるようにするためであるという．この村の人たちには，死者に対する供物という考え方は見られず，したがって，花は死者に捧げられているのではないということになる．こういった，墓の上に花を置いたりする行為を，ふだん村人が行なうことはなく，一般に墓の掃除や除草などもあまり行なわない．村の学校の生徒たちが，村の清掃をするときに，いっしょに墓地の清掃も行なうことがあるという程度で，しかも，これもかならず行なうというわけではない．

そのため，ふだん墓地では，雑草がのび放題にのびているのがふつうで，こうした雑草を目当てにしばしば家畜が墓地に入り，糞をしたり，墓を踏んだりしている．また，墓地では，子どもたちが遊んでいるのをよく見かけることがあるが（図10），彼らも墓を踏みつけているわけである．こういった家畜や子どもは，そのまま放置されているわけであるが，これは墓や墓地に対する彼らの敬意の度合いの低さゆえであると考えられる．そのほかに，あるとき墓地を訪れたら，その一画に，灯油をまいて雑草を焼いたあとが見られた．おそらく，草が枯れていたので，火をつけて除草をしたのだと思われるが，このような墓を傷つけかねないやり方には，墓地や墓一般に対する敬意は認められない．

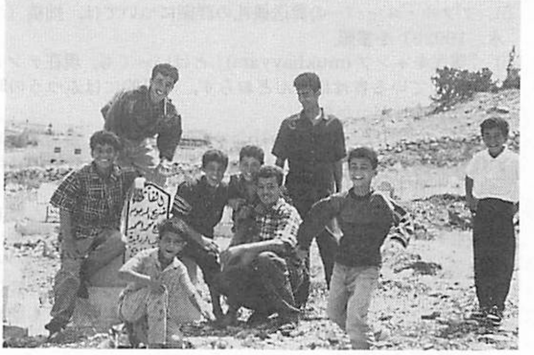

図10. 墓地で遊ぶ子どもたち．墓の上にのってポーズをとっている．(1992年クフル・ユーバーの第2墓地にて撮影)

墓や墓地に対するムスリムのこうした姿勢の背景にどのような死生観があるかということについては，既述の，日本人に見られるような「墓は死後の住処」との考え方が，ムスリムには存在しないという点を指摘することができよう．序の初めでイスラームの終末思想に言及したが，ムスリムにとって，墓はたんに終末の日の最後の審判のときまで死者の肉体が置かれているところにすぎないのである．

4. 結　　語

本稿では，農村社会クフル・ユーバー，都市社会イルビド，ベドウィンのセトゥルメントであるリーシャの3調査地の墓制について報告し，さらにその報告に主として基づきながら，アラブ・ムスリム社会の墓制と死生観の関係を中心に考察を試みた．序で述べたように，本稿は試行の域を出ないものであるが，今後補足調査を行なうことで，さらに議論を深めてゆきたい．ことに，類似の終末思想をもつキリスト教徒の墓制や死生観との比較が，興味深い課題の1つとして残る．

注

1) 本稿では，「墓制」を，「規模，立地，外観等から見た墓地 (maqbara) の様態と，色，墓地内での並び方等から見た墓 (qabr) の様態の2つを合わせたものの総体」と定義したうえで，話を進める．なお，クフル・ユーバーでも，イルビドでも，リーシャでも，墓は qabr，墓地は maqbara と呼ばれる．
2) 本稿におけるアラビア語の表記は，原則として正則アラビア語 (al-fuṣḥā) とする．
3) クフル・ユーバーを調査地に選んだ経緯については，拙著（清水，1992d）を参照．
4) 石の材質としては，花崗石に似たものなどがあるが，鉱物学的にどのような石かは不明である．

5) クフル・ユーバーの葬送儀礼の詳細については，拙稿（清水，1992b）を参照．
6) 「難民キャンプ(mukhayyam)」とはいっても，現在テントで生活している者はほとんどおらず，外見的にはふつうの町や村と見分けがつかない．
7) 本稿の主題は，ムスリム社会の墓制であるが，参考のために，本章で取り上げたイルビドの墓地のキリスト教徒の墓について，若干記述しておきたい．
墓の形態を見ると，同じ墓地のムスリムの墓とほとんど変わらない．つまり，コンクリート・ブロック等の石を長方形にならべ，なかにセメントを流し込んだものが多いのである．そのため，墓の色はほとんど灰色であり，ムスリムの墓ほど変化に富んでいない．そういう意味では，ムスリムの墓よりも簡素との印象さえ与える．
形態的にムスリムの墓と異なるのは，ムスリムの墓の nāṣib にあたるもの（何と呼ばれているかは不明）が一枚であったり，なかったりしている点である．また，墓碑については，有する墓が多いが，ない墓も見られる．墓碑の特徴は，死者の名前，死んだ日等のほかに，十字架が刻まれている点にある．なお，墓地の近くには教会や礼拝堂は存在せず，また，墓碑からは，死者が何派のキリスト教徒であるかはわからない．
8) 都市におけるムスリムの墓地一般については，拙稿（清水，1992c）を参照．
9) ルワラ族およびリーシャ，H4 の詳細については，拙稿（清水，1989, 1992a）を参照．
10) ここは，ルワラ族だけの墓地というわけではない．
11) 聖者の墓の詳細については，拙稿（清水，1984; Shimizu, 1989）を参照．
12) Musil は，チェコスロヴァキア出身の地理学者で，オーストリア・ハンガリー帝国の後援を受けて，1908年から1915年までルワラ族の調査を行なっている（前嶋，1982: 117–119）．彼の調査当時は，ヨルダン，シリア，サウディアラビアといった現在の国の区分はまだできておらず，ルワラ族のテリトリーはオスマン帝国領であった．
13) ここで考察の対象とするのは，「イスラームの死生観」ではなくて，「ムスリムの死生観」である．ウラマーが論じるような死生観（＝イスラームの死生観）に関しても，死後の霊魂の行方など，細かな点では意見の相違が見られるが，一般の人たちの死生観（＝ムスリムの死生観）となると，民間信仰的な要素が入ってくるため，地域により大きな違いが見られることがしばしばある．たとえば，筆者は，別稿で，葬送儀礼に見られるクフル・ユーバーの人々の死生観の民間信仰的な側面を指摘している（清水，1992b: 143–145）．
14) ムスリム社会の家族については，たとえば，クフル・ユーバーの家族を論じた拙稿（清水，1994）を参照．
15) ここでいう「第１墓地」，「第２墓地」というのは，筆者の命名であり，村人はこのような呼び方をしていない．
16) クフル・ユーバーの墓参慣習については，拙稿〔清水，1993: 34–40〕を参照．
17) イルビドの墓地に瓦礫と化した墓が少ないのは，番人がいて，墓を管理していることとも無関係ではなかろう．リーシャの場合はもちろんのこと，クフル・ユーバーの墓地にも，番人は存在しない．
18) ここでいう「影響力」とは，死，病気といった災いをもたらしたり，あるいは逆に，幸福や繁栄をもたらしたりするような超自然的な力を意味する．
19) 墓参慣習における慰霊の欠如および葬送儀礼のときの追善的行為における慰霊の欠如については，それぞれ別稿（清水，1992b, 145–146; 1993: 40–41）で詳しく論じた．
20) このようなムスリムの死生観については，クフル・ユーバー以外のムスリム社会からも報告なされている．
たとえば，バングラデシュの村で調査を行なった原　忠彦は，その村のムスリムの死生観について，「全般に一致している事は，死者の魂は現世の生きている人に，なんらの影響も及ぼせないということである．生者に祟るとか罰を与えるとかいうような超自然力は，神のみの所有するところであって，人間の魂などがもてるはずがない」とし，また，本稿の主題である墓制については，村人のこのような死生観との関連で，この村の場合，「立矢来がくさり，木や草が生い茂るようになると，(湿度・温度の関係で，そのようになるのに数年とかからない）墓の位置ははなはだあいまいになってしまう．村人にとって，祖父母を埋めた所を捜しだすのは，通常困難である」と述べている（原，1969: 66）．
21) たとえば，聖地マッカのように，宗教的な聖性を有するところをさす．

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Arab Muslims' Graves in Jordan

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The purpose of this article is to present a description and analysis of the Arab Muslims' graves (Arabic *qabr* (sg.)) in Jordan, with particular reference to the cases of the village of Kufr Yūbā, the city of Irbid and the Bedouin settlement of al-Rīsha. The fieldwork on which this article is based was carried out in the years 1986–1988 and in 1992.

Kufr Yūbā is an Arab village located at about six kilometers west of the city of Irbid, with a population of more than ten thousand Sunni Muslims. Although it is originally a cereal-growing village, its occupational structure is at present diversified and the agricultural population is estimated approximately at twenty percent of the total. In Kufr Yūbā a new grave is always made on someone's death. The corpse is carried to the grave and laid with the face turned in the direction of Makka in a rectangular pit lined with concrete blocks. The pit is then covered with concrete boards and with the excavated earth. The grave is mostly marked on the outside with some concrete blocks and two concrete slabs called *nāṣib* placed on the longer ends.

Irbid with its some two hundred and eighty thousand population is the largest city in northern Jordan, and is a capital of the governorate of Irbid. It houses two national universities, Yarmouk University and the Jordan University of Science and Technology. There are five cemeteries in Irbid, and the one in Tall Irbid that I have visited has a Christian section besides a Muslim section. This cemetery is surrounded by a white wall, and the Muslim section is placed in charge of a caretaker. Although the graves in the Muslim section are lined leaving no space between them, they are almost the same in shape as those in Kufr Yūbā except that the percentage of the graves with inscriptions is higher.

Al-Rīsha is located near the Syrian and Iraqi borders in the Syrian Desert. It is about forty-five minutes' drive from the small town of H4, a former pumping station of the pipeline from Kirkuk to Haifa. In al-Rīsha there are three Bedouin cemeteries, in which all the graves are only covered with the excavated earth and stones. Some graves are weatherworn and most of the earth and stones are scattered and lost.

Since the Muslims in three above-mentioned places generally take no care of the graves of the upper generation except those of their parents, all the graves are finally weathered into ruins. Their attitude of this sort to the graves originates in their view that the living does not have to maintain the friendly relations with the deceased by keeping his grave in good condition for generations to come because the latter does not affect the welfare of the former at all.

Key Words: Jordan, Arab Muslim, Death, Cemetery, Grave

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The Succession of Planted Communities in Tengeri Desert in Relation to Root Distribution and Soil Water Status

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Abstract

The field experimental results show that the succession process of planted community in Tengeri Desert sand dune is determined by the distribution of both the plant root system and available water in the soil. The results of such an interaction reveal that those species which have a near surface root system are dominant and stable component of the planted community series. The survival of a species is determined by the type of root distribution system. Shifting sand dunes can be stabilized by the planted community under non irrigation condition in Tengeri Desert.

Key Words: Root distribution, Soil water, Planted community, Succession, Tengeri Desert

1. Introduction

Tengeri Desert is the fourth largest sand desert in China and occupies an area of 36,700 km^2. The encroachment of dunes causes problems for the oasis and railway on the southeastern fringe of the desert. Since 1956, extensive desert control measures have been conducted and these schemes have proved successful. From 1959 to 1990, the oasis has been enlarged from 215 km^2 to 335 km^2 (Zhu *et al.*, 1992). Among the successful measures, the best and inexpensive way has been to establish plant community without irrigation. To meet this requirement, plant community under non-irrigated condition had been established since 1956. We call these established plant community as "planted community" to distinguish from natural community. After sand dune being fixed by the planted community, several species of herbs can naturally grow in the planted community.

The planted communities have protected the railway well for more than 30 years. However, the planted communities themselves have survived and further established. As the available water in plant root zone decreased, the habitat of plant became dry. Some of the plant population got reduced and died. Thus the total coverage of community on the old fixed sand dune decreased.

What are the main reasons to cause the succession of planted community? Will the fixed sand dune become the shifting sand dune again in the future? Scientists both in China and abroad have serious concern these questions.

To answer these questions we conducted the experiments on water status and root distribution in planted community on sand dune in Tengeri Desert.

2. Experimental Procedures

1) Characteristics of Site and Climatology

As shown in Fig. 1, the experimental field is located in Shapotou area, Zhongwei County, Ninxia Hui Autonomous Region, of China (37°32′N, 105°E). According to the meteorological data from 1956 to 1991, the annual average air temperature is 9.8℃. The average air temperature in January and July are −6.9 and 24.3℃, respectively. Annual average precipitation is 178.7 mm and 80% of the precipitation is received from May to September (1956–1991). Shifting sand dunes with a sparse vegetation are the natural landscape in this area. The coverage of the natural vegetation is

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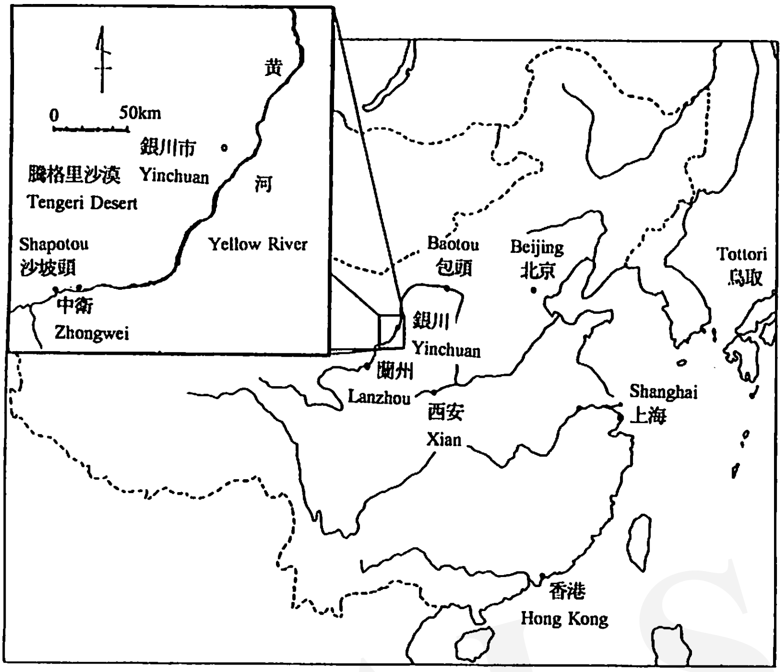


Fig. 1. Location of the experimental area.

only 1–2%. Ground water table is at more than 80 m depth and plants in this area can not use the ground water.

2) Experimental Field

There are five different experimental plots. One is the shifting sand dune. Others are four different age group planted communities which were established on shifting sand dune. Figure 2 (a) shows the natural landscape of shifting sand dunes in the study area. The high shrubs at the downright corner of Fig. 2 (a) are *Hedysarum scoparium*. The plants growing at the bottom of sand dune are *Artemisia sphaerocephala* (semi-shrub) and *Agriophyllum squarrosum* (herb). The planted communities were continuously established since 1956. Thus there are series of different age group planted communities. Two of them were shown in Fig. 2 and four of them were selected plots for our study.

We emphasize here that there are 3 common features for the planted communities series. First, all of the planted communities were established on the same type of shifting sand dune. Secondly, the plant species used to establish the planted communities are the same. The names of 3 species used are *Artemisia ordosica*, *Hedysarum scoparium*, and *Caragana korshinskii*. The first species is semi-shrub. The other two are shrubs. Besides the same species used, the arrangements of these species in the community are also the same. Thirdly, the procedures for establishing the planted community are the same. It means that the initial conditions for the planted communities series are the same. The only difference is the age group. In this study, the five selected experimental plots are:

A. Shifting sand dune;
B. 2 years old community, planted in 1987;
C. 7 years old community, planted in 1982;
D. 25 years old community, planted in 1964;
E. 33 years old community, planted in 1956.

Figure 2 (b) shows a planted community of several years old. The arrangements of species are clearly shown. Figure 2 (c) shows the planted communities of 25 and 33 years old. The central part area is 33 years old planted community. The left-upper part area is 25 years old planted community.

(a)

(b)

(c)

Fig. 2. Experimental area.
(a): the natural landscape of shifting sand dunes in Tengeri Desert.
(b): new established planted community (several years old). The original arrangement of plant species are seen.
(c): old planted communities (25 and 33 years old).

3) Experimental Period

Plant related parameters and soil water content had been continuously measured every year since 1982 in each of the experimental plots. Most of the data used in this paper were recorded in 1989. Some data recorded in 1984 are also used.

Precipitation in 1984 and 1989 was 168.3 mm and 187.1 mm, respectively. Average air temperature in 1984 and 1989 was 9.1 and 10.0℃, respectively. Both temperature and precipitation were near the annual average level. Thus data in this two years represent average level.

4) Soil Water Content

Gravimetric method was employed to note the water content in 0–3 m sand layer at an interval of 10 cm depth. The soil samples were taken every 10 days in 1984 and every 10 days from April to November and every 15 days from December to March in 1989.

5) Vegetation Investigation

The size of sample area for vegetation investigation was 10 m by 10 m. 10 samples were investigated in every experimental plot. Species composition, size of plant canopy, age structure of population, growing status, seed, and seedling were investigated in all of the samples. The coverage of community was calculated based on the size of plant canopy. The results are shown in Table 1.

6) Dominant Index

Coverage is one of the most important features for desert community and can be used as dominant index of population (Qiu *et al.*, 1991). We used relative coverage as the dominant index. The relative coverage is equal to the coverage of population divided by total coverage of community. In each experimental plot, 3 or 4 species (or groups), which are having a larger dominance index than other species, are regarded as dominant species. In different period of succession, the dominant species are different. The evolution of dominant plant species is shown in Fig. 3.

7) Root System

The data on root are cited from Liu (Liu *et al.*, 1990). Since the roots of herbs grow and distribute in the same way on fixed sand dune, all the herbs on fixed sand dune area are grouped into one.

8) Water Storage

Water storage was calculated by the following procedures. First, mass of water (m_w) was calculated by the relationship between mass water content (θ_m) and particle density of soil

Table 1. Coverage of population in the planted community series in Tengeri Desert sand dune (%).

Names of plant	Shifting dune	Planted Community series			
		2 years	7 years	25 years	33 years
Agriophyllum squarrosum	0.26	0.00	0.01	0.00	0.00
Artemisia sphaerocephala	0.22	0.00	0.79	0.00	0.00
Hedysarum scoparium	1.23	3.70	2.94	2.84	3.30
Artemisia ordosica	0.00	2.40	12.40	7.50	13.36
Caragana korshinskii	0.00	1.20	5.70	2.48	0.09
Bassia dasyphylla	0.00	0.00	1.84	0.68	1.03
Corispermum spp.	0.00	0.00	0.05	0.13	0.02
Eragrostis poaeoides	0.00	0.00	1.17	1.42	1.06
Salsola ruthenica	0.00	0.00	5.52	0.01	0.00
Total community coverage (%)	1.71	7.30	30.42	15.06	18.86

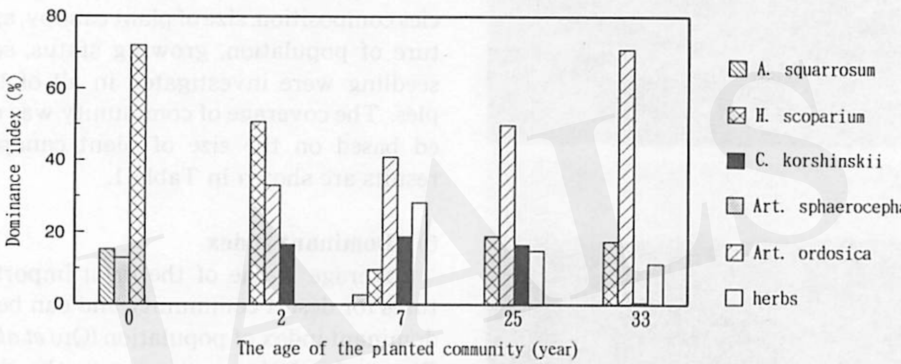


Fig. 3. Dominance index of plant species in the planted community series in Tengeri Desert sand dune.

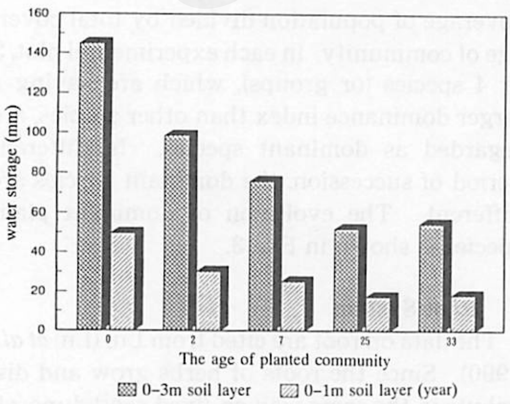


Fig. 4. The water storage in the soil of planted community series in Tengeri Desert sand dune.

(ρ_P); $m_w=\theta_m\times\rho_P\times v_s$, where v_s is the soil volume. Secondly, volume of water in the soil (v_w) is calculated by using the equation $v_w=m_w/\rho_w$, where ρ_w is the particle density of water. For unit area of soil, v_w equals the water storage in that soil layer. The water storage in 0–1 m and 0–3 m soil layer in shifting sand dune area and four selected planted community series are shown in Fig. 4. We select 0–1 m and 0–3 m soil layers because the main vertical roots of most of the plant species in this sand dune area are within 0–1 m and the vertical roots are in 0–3 m.

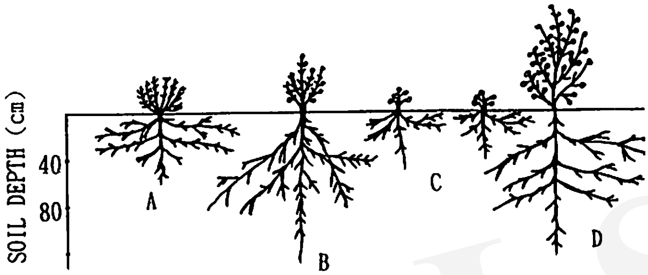
3. Results and Discussion

Generally desert plants have well developed root systems with volumes several and even 10 times larger than the above ground part (Liu *et al.*, 1990). The distribution features of root system of dominant species are shown in Table 2. The arrangement of root systems in the plant community are shown in Fig. 5. The effects of root distribution on soil water status

Table 2. The data on root system of dominant species in Tengeri Desert sand dune.

Species names	Ver.* depth (cm)	Lat.* length (cm)	Main ver. root (cm)	Main lad. root (cm)	Growth form
A. squarrosum	55	180	0–50	80	Herb
Art. sphaerocephala	150	335	150		Semi-shrub
H. scoparium	125	136	20–60	100	Shrub
Art. ordosica	65	150	0–40	50	Semi-herb
C. korshinskii	130	65	30–60	85	Shrub
B. dasyphylla	120	88	0–50	50	Herb
Corispermum spp.	45	100	0–40	75	Herb

* Ver.: is vertical; Lat.: lateral



A: Artemisia ordosica
B: Caragana korshinskii
C: Herb
D: Hedysarum scoparium

Fig. 5. The arrangement of root system of dominant plant species in the planted community series in Tengeri Desert sand dune.

in shifting sand dune area and the four selected planted community series will be discussed in detail here:

A. Shifting Sand Dune

As shown in Table 1, the coverage of community is only 1.71% in shifting dune area. From Fig. 3, we find that the dominant species is *Hedysarum scoparium*, which has a root system of 125 cm in vertical and 136 cm in lateral. Both the lateral and vertical roots are developed. Because of the sparse plant community, there are no root overlaps among species.

The water status in shifting sand dune is shown in Fig. 6. The mass water content is around 2–4%, a relatively high value in this area. The rainy season is from May to September. During and after rainy seasons, water content in the most parts of the profile is larger than 3%. Therefore it can be said that the water status in the profile is affected by rainfall.

According to the root distribution of dominant plant, we can divide the soil profile into two layers. The first is root system layer and the second layer is the soil layer below the root system. Figure 6 shows that in the root zone (0–125 cm) of dominant plant species, the

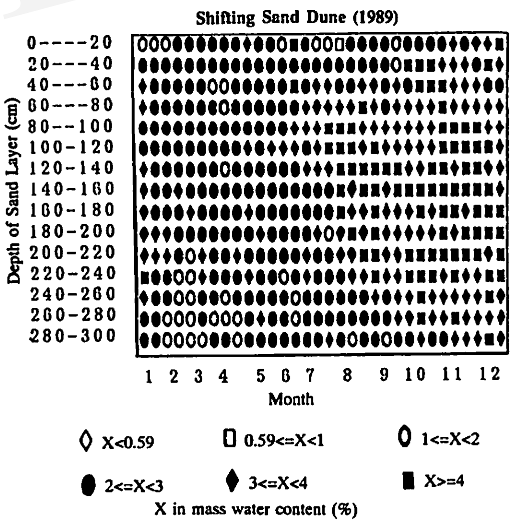


Fig. 6. Water status in 0–3 m soil layer of shifting sand dune in Tengeri Desert (From January to December, 1989).

water content is similar to the water content in the second layer. According to the growing season of plant, we can also divide the soil profile into two parts. One part is the growing season and the another part is the off season. The growing season of plant in Shapotou area is from May to September. Figure. 6 also shows that the water status for both the seasons is similar. Hence, there are no marked effects of plant roots on the soil water status in shifting sand dune area. Furthermore, because most drought resistant species can grow normally on sand dunes at a water content of 2–4%, (ZHAO, 1990), the planted communities can be established on the shifting sand dunes under non-irrigated condition.

B. 2 Years Old Planted Community

Coverage of 2 years old planted community is 7.3% (Table 1). There are only 3 plant species during this period. All of the 3 species are planted shrub and semi-shrub. *Hedysarum scoparium* has a root system with 125 cm in vertical and 136 cm in lateral. The root of *Artemisia ordosica* is 65 cm in vertical and 150 cm in lateral. Both species have a highly developed lateral roots. Lateral root of *Artemisia ordosica* distributes nearer to the dune surface than *Hedysarum scoparium*. The root system of *Caragana korshinskii* is an oblique distributed type. The main vertical roots distributed in the soil layer of 0–60 cm. From surface to deep part of soil, the appearing order of the main root system of the three species are *Artemisia ordosica*, *Hedysarum scoparium*, and *Caragana korshinskii* (Fig. 5).

Figure 7 shows the soil water status in 2 years old planted community. In most part of the profile, mass water content is between 1–3%. Few point is larger than 3% and some points are less than 1%. From Fig. 7 we also find that during and after rainy season (May to December), except the 0–20 cm soil layer, mass water content decreased. This phenomenon shows that rainfall is no more a major factor which controls the water status in 20–300 cm soil layer. However, rainfall is still one of the main factor which affects the water status in 0–20 cm soil layer.

The plant transpiration is the main factor

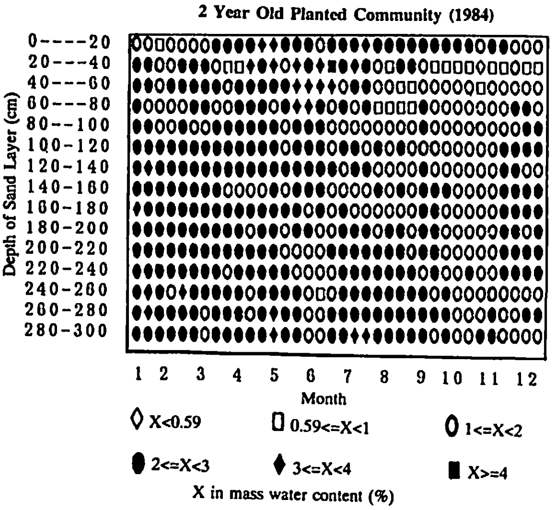


Fig. 7. Water status in 0–3 m soil layer of 2 years old planted community (From January to December, 1984).

which affects the soil water status in this period. By comparing Fig. 7 with root system of dominant species, we find that from the middle of growing season (end of June), water content in the root zones (0–130 cm) decreases to 1–2% and even less than 1% in many parts of the profile. After the growing season (November and December), the water content in some parts of the profile recovered to 2–3%. Nevertheless, in the main root system zone (0–60 cm), water content becomes less than 2% from August. Therefore, the soil water status in this period is affected mainly by plant transpiration. The water status of upper part of the soil profile is mainly affected by evapotranspiration and rainfall. Because the main root zones of the three species are infiltrated by rainfall, the planted community grows well and fast at this succession period. On the other hand, as shown in Fig. 4, the stored water in sand layer decreased fast and water received is less than water used up. The decreasing speed of stored water is the fastest in the succession series of planted community.

C. 7 Years Old Planted Community

After 7 years, planted community changed greatly. Coverage of planted community is 30.42% and reached to the maximum value in the succession series. *Artemisia ordosica*, herbs, *Caragana korshinskii*, and *Hedysarum scoparium* are four dominant species or groups. The group of herb include *Bassia dasyphylla*, *Corispermum* spp., *Eragrostis poaeoides*, and *Salsola ruthenica*. In 2 years old planted community, *Hedysarum scoparium* has the largest value of dominant index. However in this period the *Artemisia ordosica* became the most dominant species. The herbs group, invaded into the planted community naturally, became the number two (Fig. 3). The vertical roots of planted community distribute in the soil layer of 0–130 cm and the main vertical roots are in 0–60 cm soil layer. The main roots of *Artemisia ordosica*, which is the most dominant species, distribute in the soil layer of 0–40 cm. The main roots of herbs, which is the second dominant group, distribute in the soil layer of 0–50 cm. The main roots of *Artemisia ordosica* and herbs are shallower than the other species.

The water status in 0–3 m sand layer is shown in Fig. 8. Water content had decreased to 1–2% in root zone and 0.59 –1% in some parts of the profile during the growing season. However, precipitation can infiltrate through 0–40 cm soil layer for many times and infiltrate through the main root layer (0–60 cm) in July, November, and December. This is the reason why *Artemisia ordosica* and herbs are

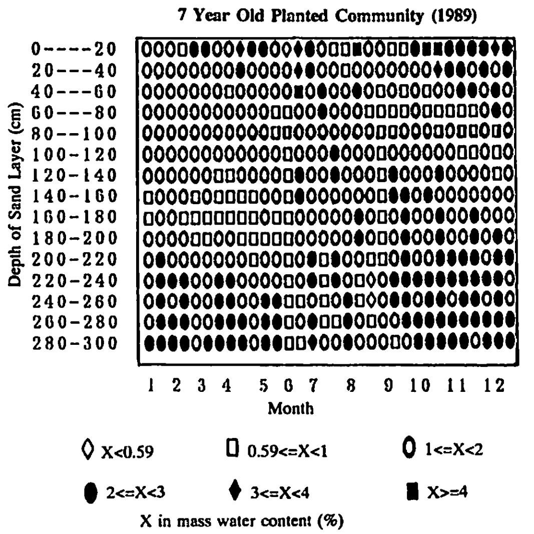


Fig. 8. Water status in 0–3 m soil layer of 7 years old planted community (From January to December, 1989).

the most dominant species because their main vertical root layers are infiltrated by rainfall.

In this succession period, because rainfall can not infiltrate through the entire root zone (0–130 cm), the deep parts of the profile (1–2 m) became dryer than the near surface parts. In the vertical direction of the main root depth, water from rainfall is first absorbed by the roots of herbs and *Artemisia ordosica*, then by the lateral root of *Hedysarum scoparium*, and lastly by *Caragana korshinskii*. *Caragana korshinskii* stopped growing and just survived in the dry habitat since less water from rainfall can infiltrate into the root zone. *Caragana korshinskii* can not propagate due to water stress. Although *Hedysarum scoparium* grows better than *Caragana korshinskii* due to its shallow level root, it can not propagate also. *Artemisia ordosica* can grow and propagate normally because rainfall can infiltrate into its root system. Herbs grow and propagate rapidly in the rainy season. During this period, the competitions for water made those species became dominant as they have a near soil surface distributed type root system.

D. 25 and 33 Years Old Planted Communities

Figure 2 (c) shows the planted communities of 25 years and 33 years old. There are two features concerned about the Fig. 2 (c). First, compared with 2 and 7 years old communities, the appearances of community changed a lot and it is hard to find the original species arrangements. Secondly, the appearances of the 25 and 33 years old communities are similar. Coverage is 15.06% for 25 years old community and 18.86% for 33 years old community. Compared with other species, *Artemisia ordosica* has a much large dominant index.

Soil water status for the 25 years old planted community is shown in Fig. 9. The wilting point of sand soil is 0.59% and these plants can survive and just grow when water content is more than 1% and can grow normally when water content is more than 2% (Zhao, 1990). From middle of April to the end of the year the water content of 0–20 cm soil layers is more than 1%. The observed rainfall infiltration is 11 times. Water content of 20–40 cm soil layer

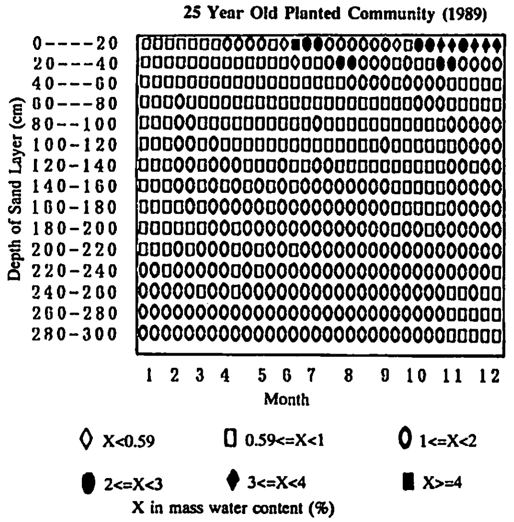


Fig. 9. Water status in 0–3 m soil layer of 25 years old planted community (From January to December, 1989).

is more than 1% from middle of July and the observed rainfall infiltration is 4 times. Water content of 40–60 cm soil layer is more than 1% only from August to the end of October. Rainfall can not infiltrate to this soil layer. Below 60 cm, there is a dry soil layer with a water content lower than 1% and persists almost all over the year. The water content in this soil layer is near wilting point and we can call this layer as "wilting layer". Rainfall can not infiltrate to this wilting layer permanently.

The main roots of *Caragana korshinskii* distribute in the soil layer of 30–60 cm. The main roots of *Hedysarum scoparium* distribute in the soil layer of 20–60 cm. Because little rainfall can infiltrate to the depth of 20 cm and no rainfall can infiltrate to the depth of 60 cm, some individuals of *Caragana korshinskii* and *Hedysarum scoparium* die due to serious water stress and other individuals of the two species survive but can not propagate. The main roots of *Artemisia ordosica* are in thesoil layer of 0–40 cm and rainfall can infiltrate to 20 cm for many times. From field observation, we find that roots of *Artemisia ordosica* get distributed nearer to surface than before to obtain more water from rainfall. *Artemisia ordosica* can produce seeds and propagate normally in the rainy season. Thus it becomes one stable component of the planted community. The main roots of herbs are in the layer of 0–40 cm or 0–50 cm and rainfall can infiltrate to the upper part of their root systems. Herbs grow and propagate normally in the rainy season and become one of the stable component of the planted community. In 33 years old planted community, *Caragana korshinskii* disappeared.

From Fig. 4 it can be inferred that the water status for the 25 and 33 years old planted communities are similar. The water storage changes no more with the increase of age. In these two periods the dominant species, which are *Artemisia ordosica* and herbs, also becomes stable component of the planted community. It means that after some period of interaction between the plant roots and water in the soil layer, the planted community has adopted to the changed condition of the habitat. Because the community dominated by *Artemisia ordosica* and herbs become stable, it will stably exist in the planted community area. Therefore dune will get fixed and the railway will be well protected.

4. Conclusions

1. The succession series of planted community in Tengeri Desert sand dune are determined by the interaction between available water in soil and the distribution of plant root system. Those species which have a near surface root distribution become stable and dominant species.

2. Because the community dominated by *Artemisia ordosica* and herbs is stable, it will exist in the planted community area in the future. Shifting sand dunes can be stabilized and railway can be protected by the planted community under non-irrigation condition in Tengeri Desert.

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中国北西部の新疆および特にトルファンにおける沙漠気候と砂丘移動

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1. はしがき

地球上の全陸地の 1/3 を占める乾燥地は地形，地質，標高などによってその特徴が大きく異なり，また気象，土壌，植生条件によっても著しい変化を示す．中国の沙漠面積は全国土の 13.6%を占める中で，中国の乾燥地，特に新疆，タリム盆地のタクラマカン沙漠やジュンガル盆地のグルバントングト沙漠の周辺部では，開発によって緑化が進む一方，沙漠化が進行している．従って，この沙漠化を防止することは欠くことのできない重要な問題である．

沙漠化には自然的なものと人為的なものがあるが，現在，主として問題になっているのは人為的な沙漠化である．砂丘地における砂の供給は，干上がった河川の川床からの移動，および特に問題なのは，再び活動を開始した古い半固定・固定砂丘からの移動であって，これらは沙漠化の最も顕在化した動態である．ゴビ（石礫）沙漠や岩石沙漠では沙漠化進行程度の顕在化は小さいが，特に砂丘地では砂の移動によって農地，牧草地，灌木林，道路，水路，民家などが砂に埋まったり，飛砂による作物，家畜や住民の日常生活への被害が出るなど，影響が顕著である．

近年，新疆生物土壌沙漠研究所吐魯番（トルファン）沙漠研究站（場）付近の砂丘は活動が活発化し，沙漠化拡大の危険性が高く，その砂丘の先端は農地に侵入しつつある．それを防止することに懸命に努力している中で，最近の植林作業が効果を果たしてきている．

砂丘の移動方向と移動速度を表した変化状況図（新疆生物土壌沙漠研究所，1978）が阿拉山口，莎車，民豊，且末，精河，莫索湾，奇台などで求められており，また耿 (1985) は克拉瑪依 (I)，于田 (II)，石河子 (III) に分割して，砂丘移動状況を形態，速度の順に，(I) 直進式（快速類），少し変動（振動・動揺）する (II) 擺動式（中・慢速類），大きく変動する (III) 盤旋式（慢速類）に区分している．しかし吐魯番では潘 (1988) の報告があるが，移動形態についての詳しい調査結果は見当たらない．

新疆生物土壌沙漠研究所 (1978) では新疆全域の砂の移動方向を求めているが，その後，かなり年数も経過しており，追加資料および再調査によって得られた修正点に基づいて地図を再編成する必要がある．

このような状況下にあって，ここでは新疆地域，および主としてトルファンの砂（砂丘）の移動について考察する．すなわち，まずトルファンで砂丘の移動速度と移動量を気象との関係から明らかにする．

次に，タリム盆地のタクラマカン沙漠とジュンガル盆地のグルバントングト沙漠における砂丘の移動方向を現地の地形，風向，ランドサットの衛星写真や新疆生物土壌沙漠研究所 (1978)，Xia *et al.* (1993) などの文献から明らかにするとともに，沙漠化の現状と進行速度の情報を得る．

さらに，沙漠化の防止，砂丘の移動防止は緊急を要する課題である．これには防風林が極めて重要な役割を果たすため，トルファンにおける 1 列と 2 列のタマリスク防風林による堆砂状況の変化を防風林の高さ，密閉度，枝張りなどの樹木の特性と気象特性との関連から明らかにするとともに，沙漠道路への保護目的に応用を検討する．

2. 調査地域の特徴および調査・解析方法

① トルファン沙漠研究站付近の砂丘地域（恰特喀勒郷のオアシスの西端）は近年沙漠化したものであり，活動の活発な砂丘では，頂上より風下側に砂粒が滑落し，砂丘の風下斜面が 33～35 度の傾斜角，安息角を持った砂丘が 1990 年には十数個あった．それらの高さは 3～8 m であり，また安息角の持つ急な傾斜の砂丘の内，大きいものでは長さ 150 m に達していた．もちろん，急傾斜面のない砂丘が大部分であるが，研究站付近の砂丘地域は南北約 2 km，東西約 5 km で，10 km^2 以上に及ぶ．また調査対象地域の風上側は砂の供給地域であって，砂丘は少なく，粘土質土壌の露出，風食地域の荒地（土漠）が広く分布しており，その面積は 60 km^2 以上である．従って，その風下側に砂が集積している．対象地域では

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（受付：1994 年 9 月 7 日，受理：1995 年 2 月 13 日）

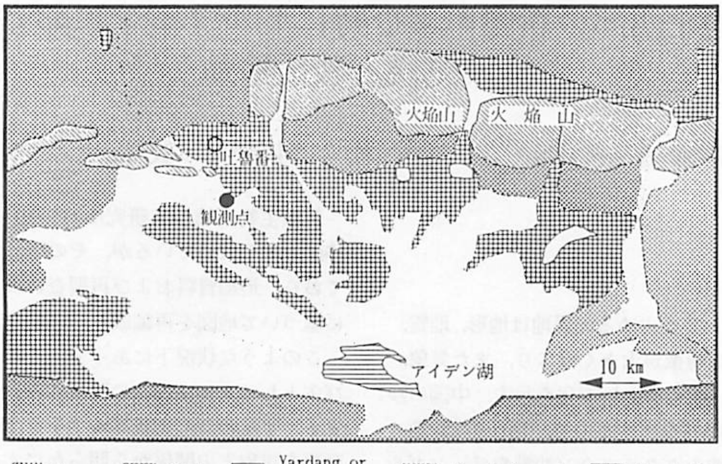

図1．トルファン沙漠研究站（場）付近の地形．

前述した通りトルファン沙漠研究站による小規模な植林によって，一部ではかなり活動が治まっているが，まだ不十分である．ここに，トルファン盆地の地形，地表の状態を図1に示す．

② 沙漠研究站の南東2～3 kmにある砂丘を用いて，1990年3月～1994年8月の4年半の砂丘移動距離と強風時間・風向との関連について調査した．調査対象の砂丘は，一方に長く尾を引く変形したバルハン型で，付近では最も大きい，高さ約7 m砂丘である．なお，このバルハン変形型の砂丘は，新疆生物土壌沙漠研究所(1978)の区分によると不対称新月形である．

③ 沙漠研究站に設定した自動気象観測装置で収録したデータを用いて，高さ6 mの強風時の風速の継続時間，最多風向を求め，強風時間と砂丘移動距離との関係を同時に求めた．気象データについては，風向，風速，気温，地温，湿度，日射量，日照時間，地中熱流量，降水量，（純放射量，土壌水分量）の観測を1990年6月より1994年まで定常的に実施しており，今後も継続するが，解析には主として1991年5月～1992年10月の期間のデータを用いた．なお風速は高さ6 mの時間平均風速が5 m/s以上の数値を採用し，風速5，10，15 m/sなどの強風時間を求めた．

④ 新疆の砂丘移動については，気候的にはかなり大きく異なる地域が含まれるが，全般的には乾燥地である新疆の砂丘地全域を対象とする．新疆の砂丘の移動状況を新疆生物土壌沙漠研究所(1978)，Xia *et al.* (1993)を参考に，各地で筆者らが4カ年にわたって砂丘の移動を調査するとともに，特に1992年11月3～11日にタクラマカン沙漠と1994年6月21～25日にグルバントングト沙漠の一周調査による沙漠化の状況，砂丘の形態・移動状況，植生分布状況，気候データなどの現地情報および人工衛星の画像写真などから新疆の沙漠における砂丘の移動方向を明らかにする．なお，活動砂丘の存在しない場所では風向を示す．

⑤ 堆砂調査には次の防風林を用いた．1列のタマリスク防風林は高さ4.6 m，林帯幅12 m，密閉度85％である．2列のタマリスク防風林は強風時の主風向に対して風上側の防風林の高さは10.0 m，風下側は5.5 mであり，それぞれ，樹高は2.5 m，4.0 m，林帯幅は19 m，13 mである．密閉度は同じく上層部50％，中・下層部100％である．なお，防風林による堆砂は平均的な地表面レベルからの高さを示す．また2列防風林の風下側の地表面は，冬季に一度灌漑する水路のため，低くなっている．

3. 調査結果

1) トルファンにおける高温期の気象特性

まず，トルファンの気候特性を知るために事例として1992年6～7月（夏季）の気象を解析した．

① 1992年6月26日～7月2日の高温期の日最高気温はそれぞれ43.5，45.7，45.4，47.9，47.8，47.7，46.3℃，最高は47.9℃で，1週間の平均では46.3℃であった．日最低気温は6月20日は14.4℃，19日は15.2℃で降雨中（6月19日）および降雨直後に出現している．なお，6月29日～7月1日の高温期の最低気温は26.7. 26.8，28.0℃で気温日較差は20℃を超えていた．なお，参考としてトルファンの冬季の気温を示すと，1991年1月5日に−18.5℃，12月28～31日に−21～

22℃であった.

② 深さ 1 cm の地温は上記の 1 週間に, 68.4, 69.6, 68.0, 66.7, 68.9, 70.4, 65.2℃ で最高は 70.4℃であった. なお, 赤外線放射温度計で測定した地表面温は 1992 年 7 月 16 日に砂丘の斜面で 84.7℃を記録した.

③ 日最低湿度は 6 月 28 日〜7 月 2 日に, それぞれ 11.8, 11.7, 10.6, 12.5, 13.4% であり, 降水量は 6 月 19 日の 5.5 mm だけであった. なお, 7 月 12〜16 日の小型パン蒸発計による日平均蒸発量は 18.2 mm で, 非常に高かった.

④ 10 分間平均の日最大風速 10 m/s 以上, または 1 時間平均の日最大風速 8 m/s 以上の日数は, 6 月に 12 日間, 7 月に 13 日間あり, 強風が 41.0% の割合で発生している. 10 分間平均日最大風速 15 m/s 以上の出現頻度は, 6 月に 2 日, 7 月に 2 日 (14 m/s 以上では 4 日) であった. 7 月 18 日の 10 分間平均最大風速は 15.91 m/s, 瞬間最大風向は 20.7 m/s, 6 月 18 日には, それぞれ 15.53 m/s, 20.4 m/s, 7 月 10 日には 15.43, 21.4 m/s, 6 月 8 日には 15.25, 20.3 m/s であった.

⑤ 強風時 (10 分間平均日最大風速 8 m/s 以上) の最多風速は 6 月に W, 7 月に WNW であり, 10 m/s 以上ではどちらも W であった.

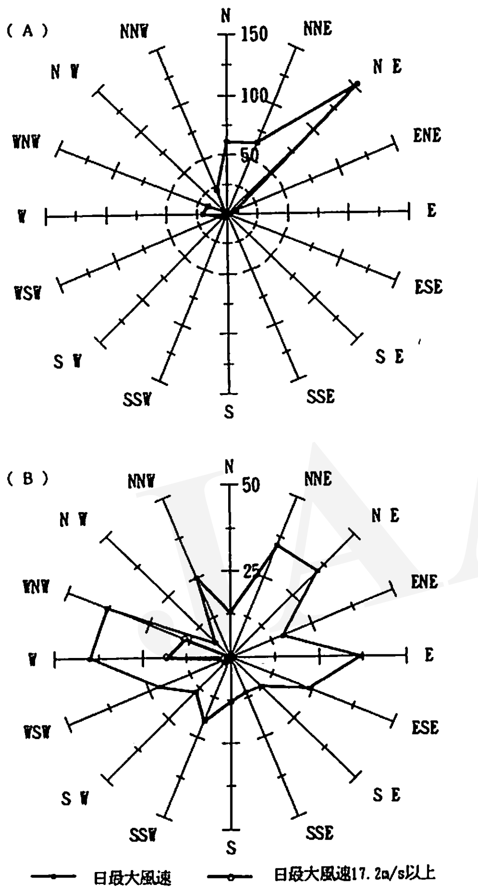

図 2. (A) 1991 年 7 月 1 日〜1992 年 6 月 30 日の風配図と最多風向 (トルファン).
(B) 同期間の日最大 10 分間平均風速と日最大瞬間風速 17.2 m/s 以上の強風の風配図と最多風向 (トルファン).

2) トルファンにおける卓越風向と強風時の風向・風速の特性

① 図 2A に風配図を示すように, トルファンの卓越風向は明らかに NE であるが, 日最大風速の最多風向では大きくばらつき, W, WNW, E, NNE, NE の順であり, わずかに W が多くて最多風向となっている.

② 図 2B に示した日最大風速が 17.2 m/s 以上の風向をみると, 最多風向は W, 次に WNW で, その他からの風はほとんど吹かない.

③ 表 1 に日最大瞬間風速の月別発生日数頻度の変化を示す. 冬・秋季は風力 3 以下の風の弱い日がほとんどで, 弱風期であり, 春・夏季の 4〜8 月は毎月 10 日前後が日最大瞬間風速 8.0〜13.8 m/s と 13.9〜20.7 m/s の区分内に入っており, 8 m/s 以上では 66.7% (2/3) を占め, この期間が強風期である. このように風速の季節変化が認められる.

3) トルファンにおける砂丘の移動方向と移動速度

(1) 砂丘移動と気候要素との関係

表 1. トルファンにおける日最大瞬間風速の月別発生日数.

風力 (風速) 月	1	2	3	4	5	6	7	8	9	10	11	12	年
3 (3.4 m/s) 未満	11	2	0	0	0	0	0	0	0	4	14	10	41
3 (3.4〜5.4)	19	24	9	7	3	2	2	7	10	16	14	18	131
4 (5.5〜7.9)	1	2	17	6	9	9	3	2	11	7	0	3	70
5〜6 (8.0〜13.8)	0	0	5	9	7	9	13	9	7	4	1	0	64
7〜8 (13.9〜20.7)	0	0	0	7	11	10	12	9	2	0	0	0	51
8 (20.8 m/s) 以上	0	0	0	1	1	0	1	1	0	0	1	0	5

観測期間: 1991 年 7 月 1 日〜1992 年 6 月 30 日 (欠測, 1991 年 8 月 18〜20 日)

1991年5月1日～1992年10月31日の10分間平均日最大風速14 m/s以上の強風時の10分間・1時間・瞬間風速，各風速の吹走時間，風向の一覧を表2に示す．また1990年9月～1994年8月のトルファン沙漠研究站付近の砂丘の移動速度と風速・風向および強風の吹走時間，砂丘の移動距離，強風継続時間，強風時の風向を表3に示す．

① 風速については，6 m高の10分間日最大風速が5, 8, 10, 12, 13, 15, 20 m/s以上の吹走時間を示した．強風は1991年7月1日以降の10分間日最大風速10 m/s以上の日数を調べると7月に12日，8月（3日欠測）に11日あった．また秋季には3日（9月12, 13日，11月4日）あったが，冬季には強風がなかった．春季の1992年4月になると急激に増えて，4月6日より春季の強風期に入り，10分間最大風速が10 m/s以上の日数が4～7月には，それぞれ7, 12, 12, 13日で，5～7月では40.2% も吹いており，強風期であることを示す．また1992年4～7月では10分間平均の日最大風速8 m/s以上の強風がほぼ2日に1回あった．なお10月に5 m/sは1時間しかなく，1992年秋季の天候の穏やかさを示す．

従って，強風頻度（表1, 2）は春季～夏季に高い．また日平均風速では内陸盆地の特性として弱いが，1日の内に，10分間平均風速8 m/s以上などの強風頻度が非常に高い特徴がある．

② 強風時（10分間平均風速8 m/s以上）の最多風向についてみると，1991年5月はWとWNW，6月はW，7月はW，8月はWNW，9月はWとWNWであり，6～8月ではW，5～10月ではWであった．また，1992年4月ではWNW，5月はW，6月はW，7月はWNW，8月はWNW，9月はWNW，10月（5 m/s以上）はWSWで，4～10月ではWであった．

図2Bのように，日最大風速の最多風向は大きくばらつくが，強風時（17.2 m/s以上）の風向はW～WNW

表2. 1991年5月～1992年10月におけるトルファンの風速，風向，強風時（10分間平均日最大風速14 m/s以上）の吹走時間.

強風時期（年月日）	10分間最大風速 (m/s)	1時間最大風速 (m/s)	瞬間最大風速 (m/s)	5 m/s以上最多風向	強風継続時間 (hr) 各風速 (m/s) 以上						
					5	8	10	12	13	15	20
1991. 5. 5	15.21	13.72	21.3	WNW	18	15	12	4	3		
5.25	14.47	12.77	24.6	WNW	13	11	10	8			
5.30	14.09	13.23	19.8	WNW	16	7	4	3	1		
6. 7	14.48	13.80	20.3	WNW	7	5	4	2	2		
6.23	14.58	12.74	18.7	W	10	6	1	1			
6.24	16. 11	15.33	22.5	W	13	12	12	6	5	1	
7. 4	14.43	13.16	19.7	WNW	12	9	9	3	1		
7.13	16.71	16.16	21.8	W	22	19	14	6	5	1	
7.18	14.02	12.59	20.0	WNW	5	4	3	2			
7.19	14.81	13.14	20.1	W, WNW	10	8	4	1	1		
8. 6	15.98	13.82	20.9	WNW	7	4	3	3	3		
8. 8	14.27	12.61	18.9	W,WSW	14	10	3	1			
9.13	14.05	12.25	18.6	W	5	5	3	2			
11. 4	15.73	11.64	22.9	W, WNW	4	3	2				
1992. 4. 9	16.14	14.92	22.1	WNW	8	6	5	4	3		
4.18	14.66	13.92	19.3	W	8	6	5	3	2		
4.25	14.76	12.68	20.6	W, WNW	9	8	6	2	1		
5. 3	16.17	15.36	20.6	W	10	9	6	6	6	1	
5. 4	14.81	13.39	19.3	W	6	5	3	3	2		
5.12	22.05	21.26	28.9	W	16	13	12	9	9	7	2
5.28	14.72	13.87	18.9	W	14	10	8	5	3		
6. 8	15.25	14.49	20.3	W	13	9	9	2	1		
6.18	15.53	12.95	20.4	W	13	12	8	6			
7. 3	14.40	13.32	19.4	W	17	15	12	8	3		
7. 4	14.39	13.03	19.2	W, WSW	8	7	6	1	1		
7.10	15.43	14.06	21.4	WNW	11	7	4	2	2		
7.18	15.91	14.93	20.7	WNW	11	10	6	3	2		
8. 2	15.12	13.68	21.7	W	7	7	6	3	2		

であった.

③ 高さ6mの風速8m/sは，高さ1mではほぼ6m/sに相当する．非常に軽く動きやすい砂では5m/sから移動し始めるが，一般的には砂の移動は大体この6m/sの風速からである．表3によると，砂丘移動は1992年5月〜7月中旬に5.0m，7月中旬〜8月には2.5m，7月中旬〜10月では3.5mであった．また1991年9月〜1992年3月の0.3mの移動のように，秋・冬季には弱風が多く，強風によって一度に多量に移動したものではない．すなわち5〜6m/sの風（高さ6m）では砂丘の移動への関与の程度は小さく，10m/s以上の風に依存する程度が大きい．

④ 表3に示すように5, 8, 10, 12, 13, 15m/sを基準として，それ以上の風速(m/s)の発現時間(t, hr)と砂丘の移動距離(d, m)との関係を求めた．1991年9月1日〜1992年8月31日には，それぞれ次式のようになった．

$d=0.0177\,t$, $d=0.0356\,t$, $d=0.0687\,t$, $d=0.141\,t$, $d=0.225\,t$, $d=1.125\,t$

0.0177などの比例係数(k)と風速(u, m/s)には次式の通りベキ関係があり，相関係数(r)は0.918であった。

$$k=4.63\cdot10^{-5}u^{3.38}$$

その他の期間についても同様な関係があり，ベキ乗は2.09〜3.38で，平均3.02であった。ただし，1992年4月1〜30日は短時間で他とかなり異なるため除くと，2.98〜3.38で，平均3.18となった。なお，全体のrは0.917〜0.985で，平均は0.952で非常に高い。

ここで，移動距離(d, m)，吹走時間(t, hr)，風速(u, m/s)を考慮すると，

$$d=7.3\cdot10^{-5}t\cdot u^{3.18}$$

で表わせる．従って，砂丘は風速のほぼ3乗に比例して移動することになる．この関係式によると，強風の継続時間と砂丘の移動距離は5, 8, 10, 12m/s以上の強風とかなり対応するが，長期間になれば平均的な8〜10m/s

表3．トルファンにおける風速，風向，砂丘の移動距離，強風時の吹走時間および吹走時間に対する移動距離の比率（係数）．

期間（年 月 日）	風速 (m/s) 5	8	10	12	13	15	20	砂丘移動距離	強風時の主風向
	上段：	吹走時間 (hr)，		下段：	係数 (cm/hr)				
1990年9月〜1991年8月								年間移動 9.5m	風向 W〜WNW
1991年5月1日〜1991年8月31日	451 1.55	215 3.26	123 5.69	46 15.22	15 46.67	1		7.0m	W
1991年9月1日〜1992年3月31日	38 0.79	9 3.33	6 5.00	2 15.00				0.3m	W
1992年4月1〜30日	51 2.35	27 4.44	19 6.32	10 12.00	6 20.00			1.2m	WNW
1992年5月1日〜7月12日	279 1.79	160 3.13	85 5.88	43 11.63	27 18.52	8 62.5	2	5.0m	W
1992年7月13日〜8月31日	140 1.79	56 4.46	21 11.90	9 27.78	7 35.71			2.5m	WNW
1991年9月1日〜1992年8月31日	508 1.77	253 3.56	131 6.87	64 14.06	40 22.50	8 112.5	2	年間移動 9.0m	風向 W〜WNW
1992年9月1日〜10月31日	52 1.92	18 5.56	8 12.50	3 33.33	3 33.33			1.0m	WNW
1992年11月1日〜1993年8月5日								11.0m	W〜WNW
1992年9月〜1993年8月								年間移動 12.0m	風向 W〜WNW
1993年9月〜1994年8月								年間移動 11.0m	風向 W〜WNW

の強風とよく対応する。

⑤ 1991年5月1日～1992年10月31日の内，5 m/s の場合の比例係数 k と吹走時間 t との関係をみてみよう。ただし，1991 年 9 月～1992 年 8 月の 1 年間では平均的な値となるので除外すると，r は 0.964 で，期間が長くなれば減少する傾向があるが，8, 10 m/s では r は 0.568, 0.524 と相関は低い．

このように短期間よりも長期間の係数が小さくなることは，長期間では逆向きの風も関与して移動量が減少するため，結果的には移動距離は短くなることを示す．冬季には長時間の弱風と風向変化の影響が大きく作用することや，この場所特有の現象，あるいはこの期間の区分の仕方によって生じた現象とも考えられるため，今後検討を要するが，トルファンでは上述の傾向が認められた．

1992 年 5 月～7 月中旬における 5 m/s 以上の場合の比例係数 1.79 は，7 月中旬～8 月のそれと同じであるが，10 m/s 以上の比例係数では小さい．これは前者の 2.5 カ月は後者の 1.5 カ月より長いが，10～13 m/s の強風の割合が高いために単位時間の移動距離が相対的に小さく，後者の方が強風による単位時間の移動距離が大きいことを，または前者の 15, 20 m/s の強風が砂丘移動に大きく寄与することを意味する．また，1991 年 9 月 1 日～1992 年 3 月 31 日では 10 m/s 以上は 9 月 12，13 日と 11 月 4 日しかなく，相対的に弱風の 5 m/s 程度の吹走時間が長いことが関連して，5 m/s 時の係数が小さくなっている．

(2) 実際の砂丘の移動方向と移動速度

① 1991 年 5 月～1992 年 10 月の 1 年半の砂丘の移動方向とベクトル表示の月別の移動距離（8 または 10 m/s 以上の基準風速と吹走時間との積で示した距離で，風向を考慮して図化）を図 3 に示した．1991 年 5～8 月では移動距離は 7.0 m であり，主として東方であるが，わずかに南方成分をもって移動した．また 1991 年 9 月～1992 年 8 月の 1 年間では 9.0 m 移動し，この期間も主として東方であるが，6～8 月には西南西の風が西北西の風より多いため移動方向はわずかに北方成分をもつが，1992 年 9～10 月には再びわずかに南方成分をもって移動した．すなわち暖候期の強風期間でも年により若干異なることがあるが，2 回の強風期を含めた 1 年半では東方よりわずかに南方に寄って移動したことになる．

② 砂丘の移動方向は強風時の風向に従って，W～WNW 方向からの移動であった．ただし時期によって，すなわちその時期の W または WNW などの風向によって，その方向が少し変わるが，W～WNW の範囲には変わりがなく，また 1993, 1994 年 も同じ W～WNW であった．

従って，砂丘は W～WNW 方向から E～ESE 方向に移動することになり，実際には，図 3 に示すように，その両方向の中間的な東寄りの移動方向である．

③ トルファンの高さ 7 m の砂丘の移動距離は 1990 年 8 月～1991 年 8 月に 9.5 m，1991 年 8 月～1992 年 8 月に 9.0 m，1992 年 8 月～1993 年 8 月に 12.0 m，1993 年 8 月～1994 年 8 月に 11.0 m で，平均では 10.4 m であった．これについては考察で述べる．

4) 新疆全域の砂丘の移動方向

新疆地域の砂丘の移動方向を新疆生物土壌沙漠研究所 (1978)，XIA *et al.* (1993) の図を基礎にして，1990～1994 年の筆者らの調査を加えて修正・編成した結果を図 4 に示す．後述するタクラマカン・グルバントングト沙漠調査で明らかにしたもので，主な修正点はタクラマカン沙漠南端部では，民豊 (Minfeng, Niya) から牙通古斯闌干 (Yawatongguzlangar) の地域，特に牙通古斯闌干寄りが砂丘の移動方向の変更地点であると判断される．次にトルファンでの移動方向の細分化を行ない，主として西～西北西風によって東方寄りに移動することおよびトルファン東部の鄯善 (Shanshan，シャンシャン)

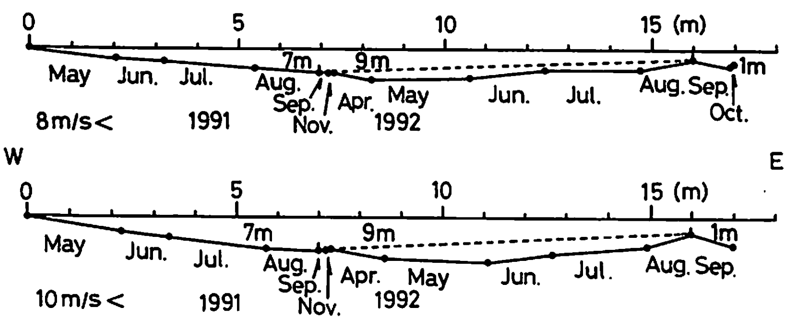

図 3. トルファンにおける 1991 年 5 月～1992 年 10 月の砂丘の移動方向とベクトル表示の月別移動距離．
（上） 8 m/s 以上，（下） 10 m/s 以上

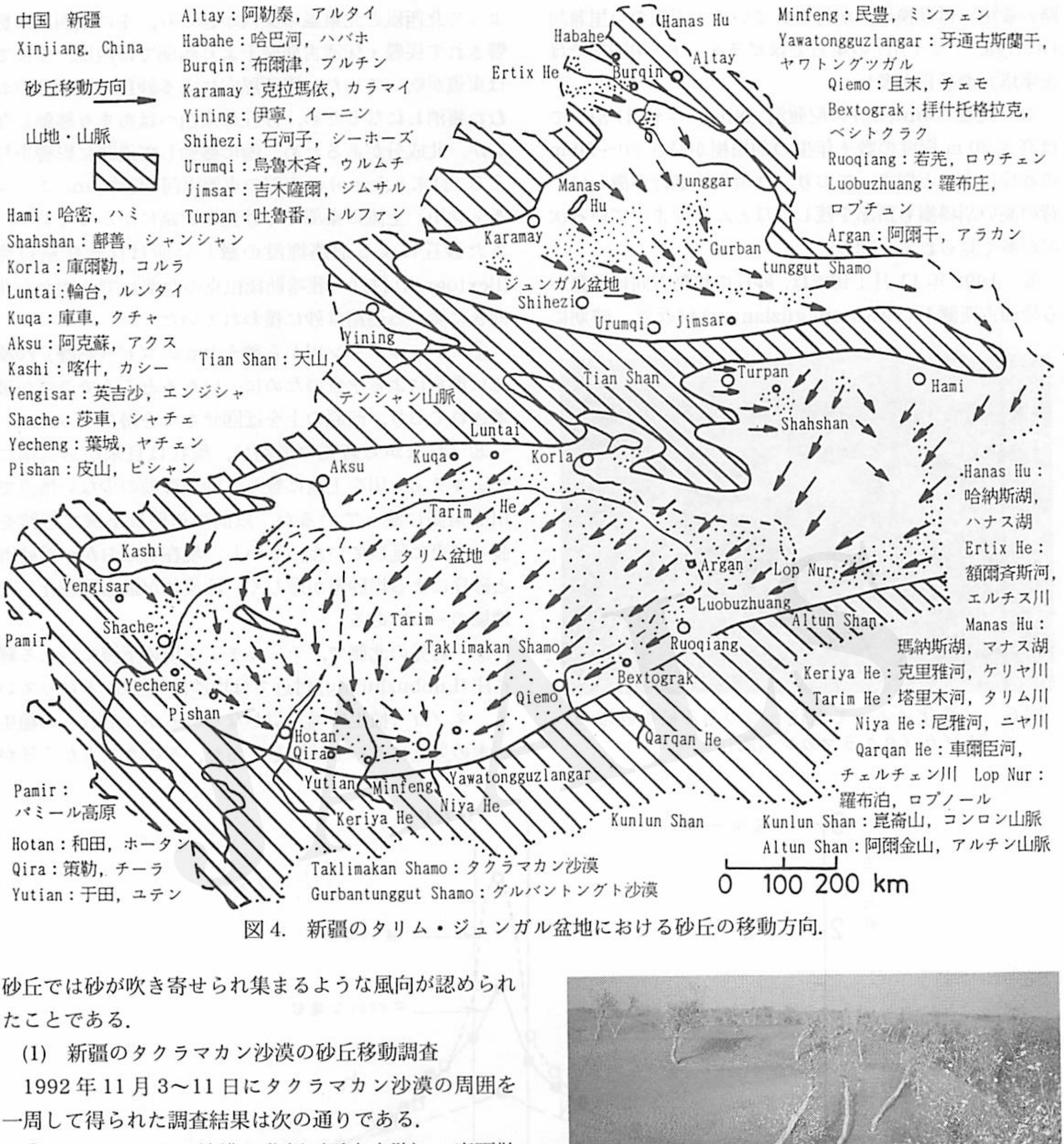

図 4. 新疆のタリム・ジュンガル盆地における砂丘の移動方向.

砂丘では砂が吹き寄せられ集まるような風向が認められたことである.

(1) 新疆のタクラマカン沙漠の砂丘移動調査

1992 年 11 月 3～11 日にタクラマカン沙漠の周囲を一周して得られた調査結果は次の通りである.

① タクラマカン沙漠の北側（天山南路）の庫爾勒 (Korla) から喀什 (Kashi, Kaxgar カシュガル) 間の風向は阿克蘇 (Aksu)・庫爾勒間と阿克蘇寄りが北東，喀什付近が北西であるため，砂丘は幹線道路からはほとんど見られず，タリム川付近以南に砂丘がある.

② 喀什から南に下ると砂丘が増加し，英吉沙 (Yengisar), 莎車 (Shache, Yarkant ヤルカンド) では道路沿いにも見られるようになる. さらにタクラマカン沙漠の南側，崑崙（Kunlun, コンロン）山脈の北側，葉城 (Yecheng), 皮山 (Pishan), 和田 (Hotan) の北側では，ほとんどの地域で砂沙漠か，ゴビ（石礫）沙漠である.

③ 和田，策勒 (Qira) の北側では砂丘が多く，特に策勒の一部では道路を越えて南側に高さ 20～30 m の砂丘，北側には 50 m の砂丘がある.

図 5. 押し寄せて来る砂丘に埋没しつつある胡楊樹（民豊の尼雅川沿い）.

④ 于田 (Yutian) から若羌 (Ruoqiang, Qarkilik チャルクリク) にかけては砂丘で道路が埋まるため，道

路の変更（付け換え）が行われている．于田の克里雅河（Keriya，ケリヤ川）の東方ではピラミッド（中国語では金字塔）型砂丘が多い．

⑤　民豊（Minfeng）の尼雅河（Niya，ニヤ川）沿いでは高さ 20 m 程度の数十年生の胡楊樹が高さ 20～30 m の砂丘に次々と埋まっており，沙漠化の進行が激しい．背の高い胡楊樹も頂部を残してほとんど埋まっている状況が多く見られる（図 5）．

⑥　1992 年 11 月上旬では，砂丘の移動方向は民豊から牙通古斯蘭干（Yawatongguzlangar）付近で，時期によって北西風と北東風の交代が起こり，主に東西風に影響されて民豊・牙通古斯蘭干より西部では西風，東部では東風が吹いていた．東西風向による砂丘の移動はおおむね帳消しになるため，砂丘は東西へはあまり移動しないが，北成分があるため，南に移動して道路に影響を与える．且末（Qiemo）の南部の車爾臣河（Qarqan，チェルチェン川）上流の東部では砂丘が道路にかかっており，また砂丘による道路埋没の激しい所は拝什托格拉克（Bextograk）付近（雅喀勒托拉克の西部）で，南から北向きに変わる道路は砂に覆われていた．

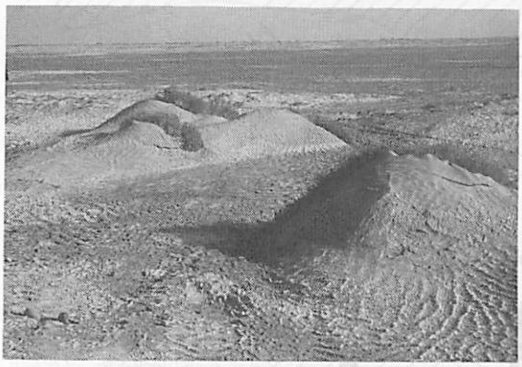

図 6.　沙漠化によって退化しつつある植生砂堆のネブカ（タクラマカン南部）．

⑦　チェルチェン川から数十 km のゴビ（石礫）沙漠では洪水による水食のために，いたるところで道路が破壊されており，河原の上を迂回せざるを得なかった．

⑧　且末から若羌の道路は，現在は且末から真南にチェルチェン川を上流に登り，砂丘移動の少ない地点で川を東側に渡っているが，以前の道路は下流で道路を渡って東に延びていた．しかし，現在もなおかつ飛砂害と砂丘による堆砂害が激しく，沙漠化が最も顕在化した地域の一つである．

⑨　若羌の北側で，チェルチェン川の下流に当たる羅布庄（Luobuzhuang）付近では塩沙漠（図 6）となっている．ネブカ（植生砂堆）がかなりあるが，それらの植生が水の欠乏によって枯死しており，そのネブカから砂が

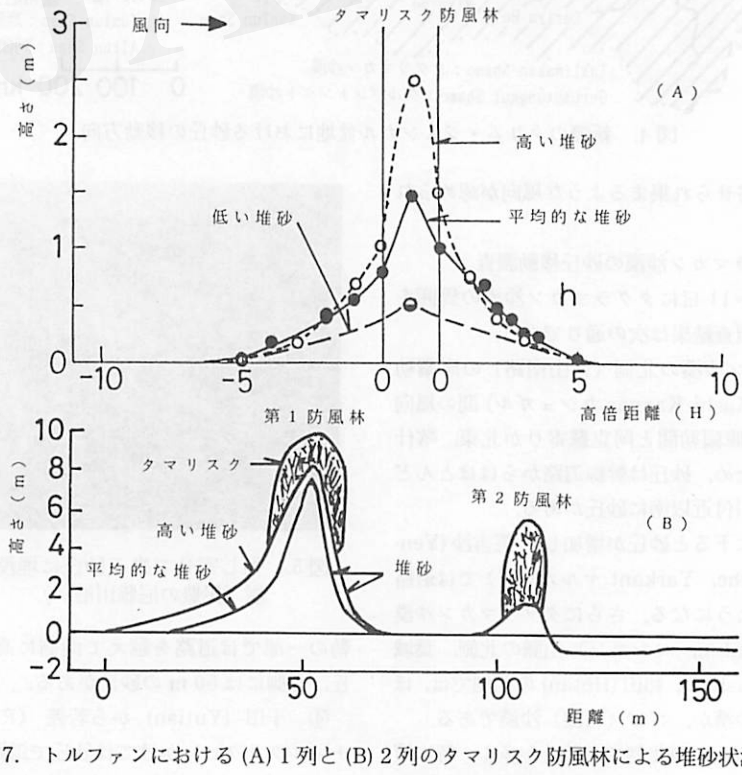

図 7.　トルファンにおける (A) 1 列と (B) 2 列のタマリスク防風林による堆砂状況．

供給されている場合もかなりあり，沙漠化が進行している．なおネブカ（図6）とは，植物が生えると風を遮るため砂が堆積するが，堆砂するとその植物は埋まるので，上方に伸張して高くなり，また砂が堆積する，この繰り返しでできた植生の砂塚である．水分の欠乏によって植物が枯れると砂塚は風食を受けて消失する．

⑩　若羌・庫爾勒間の阿爾干(Argan)付近の南北100 km程は非常に古い胡楊樹林帯となっているが，塔里木河（Tarim，タリム川）の西側まで砂丘が迫っている．これらの中で，胡楊樹は老齢化し，かなり枯死している地域もあり，沙漠化が心配される．なお，この町は農場を拡大して新興農村都市となっているが，これはタリム川を羅布泊(Lop Nur，ロプノール）の方に流さず，南方のこの地域に流している結果である．しかし，それにしても上流での水の消費やダムのために水量は減少しており，節水，すなわち水の損失を軽減する土木的工事が必要である．また一方，胡楊樹の保護も不可欠である．

(2)　新疆のグルバントングト沙漠の砂丘移動調査

①　1994年6月21～26日にジュンガル盆地を縦断して調査を行った．烏魯木斉（Urumqi，ウルムチ）を出発して，グルバントングト沙漠南端付近の吉木薩爾(Jimsar，ジムサル）からジュンガル盆地の中央部東寄りをほぼ直線的に北方に進み，阿勒泰（Altay，アルタイ）から布爾津（Burqin，ブルチン）と哈巴河(Habahe，ハバホ）を通って哈納斯(Hanas，ハナス，哈巴河北東部のロシア国境近くの氷河湖）に行き，哈納斯からは布爾津を通って中央部西寄りを克拉瑪依（Karamay，カラマイ）まで南西に下って，克拉瑪依北東部にある瑪納斯湖（Manas，マナス湖）寄りの沙漠道路を通ってウルムチへ帰るコースを取った．これらの沙漠道路は兵団の軍事・農業用および主にジュンガル盆地の石油開発用に建設した道路である．

②　ジュンガル盆地中央部の南部寄りに砂丘地域があるが，東部寄りの沙漠道路では半固定砂丘が多く，一部に活動砂丘がある．また西部寄りの沙漠道路では南部に半固定砂丘があり，最近活動を再開した砂丘も一部に認められる．さらに布爾津西部の額爾斉斯河（Ertix，エルチス川）南岸と北部の山寄りにも砂丘が少しある．

5)　防風林・ネットによる防風・防砂効果

(1)　トルファンにおける防風林による風食・堆砂状況と微気象特性

1列のタマリスク防風林による堆砂状況は，図7Aに示す通りである．堆砂の厚さは高い所で2.5 m，平均的な所で1.5 m，低い所で0.5 mであり，タマリスクの細かい枝葉による濾過作用が堆砂を促していると考えられる．

図8．防風ネットと碁盤目状の草方格（タクラマカン中北部）．

2列のタマリスク防風林による堆砂状況は図7Bに示す通り，主風向に対して風上側が高さ7.5 m，風下側が高さ1.5 mである．また，これらの防風林による減風，日中の気温・地表温降下，湿度増加の効果が認められた(真木ほか，1992, 1994)．乾燥地での加湿は微気象改良に有効であり，特に朝夕の加湿の効果は大きい．このように防風林は気候緩和，風食・飛砂防止，砂丘移動防止，さらに作物栽培に好適な環境改良などの機能を持つ．

(2)　タクラマカン沙漠の沙漠道路と防風ネット

タクラマカン沙漠（タリム盆地）の石油開発の目的で，現在，沙漠道路を建設中であるが，砂丘地域では，飛砂・堆砂防止を行う必要がある．そこでトルファンで実施した防風林，特に防風ネットによる風食防止・堆砂効果（真木ほか，1993）が評価されているので，その防風ネットを応用して試験を行った．輪台（Luntai，ルンタイ）の南100 km付近のタクラマカン沙漠内に2 kmの試験道路を建設し，レンガ，コンクリート，アスファルト，塩散布などの各種の試験を実施している．その道路を保護するために，草方格（ワラ，ヨシなどを1 m×1 mの碁盤目状にシャベルで砂中に押し込み防風・防砂を行う高さ10～20 cmの簡易な施設，幅100 m，図8），防風垣（高さ1～2 mのヨシ束垣，ヨシズ垣など），防風ネット（高さ1～2 m）などで，防風・防砂効果の評価を実験している．

この防風ネットによる試験結果では，トルファンでの物理的，気象的評価結果（真木ほか，1993, 1994）と同様に効果が大きかった．しかも日本製（ポリエチレンラッセルネット，2 mm目，密閉度30～40%，高さ2 m，長さ100 m: 図8）と中国製（密閉度50～60%）のネットを用いているが，日本製は密閉度が比較的低く，繊維が細いため，通風が比較的大きい割に，防風効果が大きい特徴があり，さらに設置した防風ネットは砂に埋没し

たり，逆に支柱が掘れて倒れたりすることが少なく，より有効であった．この成果を試験段階から実施段階に持ち込むため，長さ 5 km 程度の本格的なネット設置によって判定する予定であり，その効果が期待される．

4. 考察

(1) トルファン沙漠研究站付近の最近の砂丘移動

潘(1988)がトルファンで求めた 1973～1978 年の砂丘移動距離は，年間で平均 28.1 m であり，速い年には 67.5 m，遅い年には 10.0 m であった．また，1959 年当時は高さ 4～6 m の活動砂丘が 34 個あり，最も高い砂丘の高さは 7 m であった．これらの結果を比較すると，活動砂丘は減少し，最近数カ年の移動は非常に遅くなった．この理由として考えられることは，砂丘の高さとその横幅の違いがあること，すなわち本報告の砂丘はバルハン型砂丘から横列砂丘に変形するものであり，急斜面の広くなった，対象地域では大規模な砂丘（同じ高さ 7 m）を対象にしていること，潘(1988)の報告では独立した砂の供給の比較的少ない典型的なバルハン型の砂丘であり，砂の容積が小さいことも関与していると考えられる．しかも，最も大きい理由としては，砂丘の移動を抑えるため，沙漠研究站の最近の植林による努力の結果である．

以上が砂丘の移動を小さくしている理由と考えられる．この地域は，広範囲に見ると沙漠化しているにもかかわらず，主風向に対して風下側に当たる沙漠研究站の南東 2～3 km 付近の砂丘移動に限定すると，結果的には明らかに治まりつつあると結論付けられる．

(2) トルファン沙漠研究站付近の沙漠化の緩和状況

1994 年の調査から判断すると，沙漠研究站での植林による効果と 1993 年の異常気象（低温，多雨）の影響が大きいと考えられる．また調査対象砂丘も，ここ数年間は，砂丘の高さについてはそれほど変わらないが，規模がかなり小さくなっている．さらにバルハン型（変形も含む）の活発な砂丘は減少しており，5 年前には付近に十数個あったが，1994 年現在では 5～6 個に減少している．ただし，小規模な砂丘の活発化（急な安息角を示す砂丘）は多く見られる．なお，1993 年の異常気象による影響は沙漠植物を活性化させ，砂丘移動の減少に一役かっていると考えられる．なお，1994 年も 7 月までの沙漠植物の活性は旺盛であった．

5. まとめ

中国北西部の新疆，主としてトルファンにおいて沙漠化と乾燥気候の関係，砂丘の移動，防風林による堆砂などの調査を行った．得られた主な結果は次の通りである．

(1) トルファンでは秋・冬季は弱風期，春・夏季が強風期である．春季の強風期には高さ 6 m の日最大瞬間風速 8 m/s 以上が 67%，10 分間平均の日最大風速 10 m/s 以上が 41% であった．また，夏季の高温・乾燥期の気温，湿度の特徴を明らかにした．

(2) トルファンの最多風向は NE であるが，10 分間最大風速では W, WNW, E, NNE, NE が多く，ばらつきが大きい．強風時（10 分間平均の日最大風速 8 m/s 以上，または日最大の瞬間風速 17.2 m/s 以上）の最多風向は W，次いで WNW であり，砂丘は E～ESE 方向，すなわち東寄りに移動する．

(3) 沙漠化によって形成されたトルファンの砂丘について，1991 年 5 月～1992 年 10 月の移動速度と風速・強風吹走時間との関係，および砂丘が風速の 3 乗に比例して移動することを明らかにした．

(4) トルファン沙漠研究站付近の高さ 7 m の砂丘について，1990 年秋季～1991 年夏季から 1993 年秋季～1994 年夏季までの 4 年間の移動距離は，それぞれ 9.5 m, 9.0 m, 12.0 m, 11.0 m であり，平均値は 10.4 m であった．この付近では沙漠化は進行しているが，風下側最先端における砂丘移動に限定すると，主として植林によって治まりつつあると考えられる．

(5) 新疆のタクラマカン沙漠とグルバントングト沙漠について，最近の砂丘の移動方向を図化した．タクラマカン沙漠南端では民豊から牙通古斯蘭干付近にかけての地域が砂丘の移動方向の変更地点であると判断された．

(6) 乾燥地トルファンにおける防風林は気象改良効果が大きく，また風食防止，堆砂作用が大きいことを明らかにした．

(7) 1992 年秋季時点では，タクラマカン沙漠南部域における砂丘移動による沙漠化進行が大きいこと，また飛砂，風食，水食の発生や道路への影響状況を記述した．

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Relation between Desert Climate and Movement of Sand Dunes Particularly at Turpan in Xinjiang of Northwestern China

Taichi Maki*, Borong Pan**, Mingyuan Du*** and Ryoji Sameshima***

Relations among desertification, arid climate, movement of sand dunes, sand accumulation by windbreaks and so on were investigated at Turpan in Xinjiang of Northwestern China. Obtained results are mainly as follows:

(1) The periods of strong and weak winds are from spring to summer and from autumn to winter, respectively. The appearance frequencies over 8 m/s of daily maximum instantaneous wind speed and over 10 m/s of daily maximum 10-minute mean wind speed at a height of 6 m were 67% and 41%, respectively. The characteristics of air temperature, soil temperature and humidity at the dry period of high temperature in summer were made clear.

(2) Prevailing wind direction at Turpan is E direction. The most frequent wind direction of daily maximum 10-minute mean wind speed is W, however, wind directions are scattered to W, WNW, E, NNE and NE in the order. The most frequent wind direction over 8 m/s of daily maximum 10-minute mean wind speed is W, and the second is WNW. Moving direction of sand dunes is the direction from E to ESE, *i. e.*, close to E direction.

(3) It was shown in the tables that relations among the moving speed of sand dunes based on desertification, the grade of wind speed and blowing duration of strong wind at Turpan at the period from May, 1991 to December, 1992, and that movement of sand dunes is in proportion to the third power of wind speed.

(4) The moving distances of the 7 m high sand dune near Turpan Desert Research Station were 9.5, 9.0, 12.0 and 11.0 m at every one year from autumn in 1990 to summer in 1994, and the average was 10.4 m. The desertification around the region has been expanding, however, moving sand dunes themselves have been decreased mainly by the windbreak trees recently planted at the leeward edge of the desert.

(5) The recent movements of sand dunes were figured in Taklimakan Desert and Gurbantunggut Desert, Xinjiang, China. The changing point of the moving direction of sand dunes were found in the area of Minfeng and Yawatongguzlangar at the south of Taklimakan Desert.

(6) Windbreak forests are effective in meteorological improvement, prevention of wind erosion and sand accumulation at Turpan which is located in the arid land.

(7) In autumn, 1992, the expansion of desertification at the south Taklimakan is severely affected by moving sand. The situations of wind erosion, water erosion, blowing sand and their effects on roads were introduced.

Key Words: Arid climate, China, Desert, Desertification, Sand dune, Wind, Windbreak

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中国タクラマカン砂漠における気象要素の長期観測

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1. はじめに

現在，地球上の砂漠・乾燥/半乾燥地域の総面積は6,000万 km^2 以上に及び，全陸地面積の約1/3を占めるに至っている．さらにこの面積は年々かなりの割合で増加しつつある (UNEP, 1992)．したがって，砂漠化問題は，世界人口の増加と相まって，人類の将来に関わる緊急かつ深刻な地球環境問題として国際的に認識されている．近年の砂漠化の急激な進行は，過放牧や伐採など主に人間活動によって引き起こされていると考えられているが，このような人為的な原因による砂漠化で生じた地表面条件の変化によって，周辺地域の環境がどのような影響を受けるのかについては不明の点が多い．

砂漠化防止に関しては，従来から各国において種々の対策が講じられてきたが，砂漠化の問題は非常に多くの要素が関係した複合的な問題であるため，その成果は必ずしも十分には上がっていないのが現状である．したがって，砂漠及びその周辺地域の環境に関して，気圏・地圏・水圏・生物圏等多くの分野から，地球科学的観点に立った総合的な調査研究を行う必要がある．特に，砂漠あるいは砂漠化しつつある地域における気象条件，特に地表面付近の大気の構造は，十分には把握されていないのが実状であり，乾燥・半乾燥地域を対象とした気象学・気候学的調査研究が必要とされている．

日本においても最近になって砂漠研究の重要性が認識され，科学技術庁によって中国タクラマカン砂漠を対象として日中共同研究「砂漠化機構の解明に関する国際共同研究」が平成元年度より実施されている．中国においては17万 km^2 の地域で砂漠化が進行しており，さらに16万 km^2 の地域が潜在的に砂漠化の危機にさらされている (Zhu and Lin, 1983)．これは中国全土の約3.5%に相当し，中国の農業に大きな影響を与えている．特に中国北西部の新疆ウイグル自治区にあるタクラマカン砂漠は，東西約1,000 km，南北約400 km，面積約33万 km^2（日本の面積の約86%）の大きさを持ち，天山・崑崙の両山脈に南北を挟まれ，西にはパミール高原が存在するタリム盆地の主要部を占める中国最大（世界第2位）の砂漠である．この砂漠では流動砂丘が優勢で，流砂が砂漠面積の85%以上を占めると言われている（任, 1982).

タクラマカン砂漠の気候条件については，砂漠周辺部については不十分ながらも観測資料があり，長年の気象観測資料の統計値に基づいて，気候状況が明らかにされている（例えば，新疆地理学会, 1993)．これらの資料によれば，年降水量は，北西縁で50〜80 mm，南東縁で20〜30 mmで，今回観測を実施した南縁の和田地区では33.5 mmとなっている．しかし，気象観測点はオアシス内にあるため（この報告においてはオアシスを単なる小さな水面だけでなく，その周囲の農地などを含めた広い意味で使用している)，周囲の砂漠との植生や地表面条件の相違などにより，得られた風・気温・湿度等の気象要素は砂漠とは異なっている (Inoue and Mitsuta, 1990)．さらに観測回数が1日3〜4回であるため，気象要素の日変化等については詳しいことはわからない．したがって，砂漠気候の実体を把握するためには，砂漠の代表的な地表面条件であるゴビや砂砂漠上において，長期間にわたる気象観測を行なう必要がある．

砂漠における地表面付近の大気の状態を明らかにするために，著者らは1991年11月より中国北西部のタクラマカン砂漠のゴビ上に自動気象ステーションを設置し，気象要素の長期自動観測を実施している．今回の共同研究においては，砂漠における熱収支・水収支の実態を解明することが重要な目的であるため，気象観測に加えて，地中温度や土壌水分さらには土壌物理要素の観測なども併せて実施している．

ここでは，長期観測によって得られた気象資料（地表面温度なども含む）を用いて，タクラマカン砂漠の気候の基本的特徴について解析した結果を示す．

2. 観測の概要

1) 観測地点

観測地点（北緯36°55′35.5″，東経80°47′9.2″:北京標準時との時差は2時間37分）は図1に示すように，タクラマカン砂漠南縁のオアシス都市和田（ホータン：人口約32万人）から東に100 kmほど離れた小さなオアシス策勒（チーラ：面積33千 km^2，人口約11万人)

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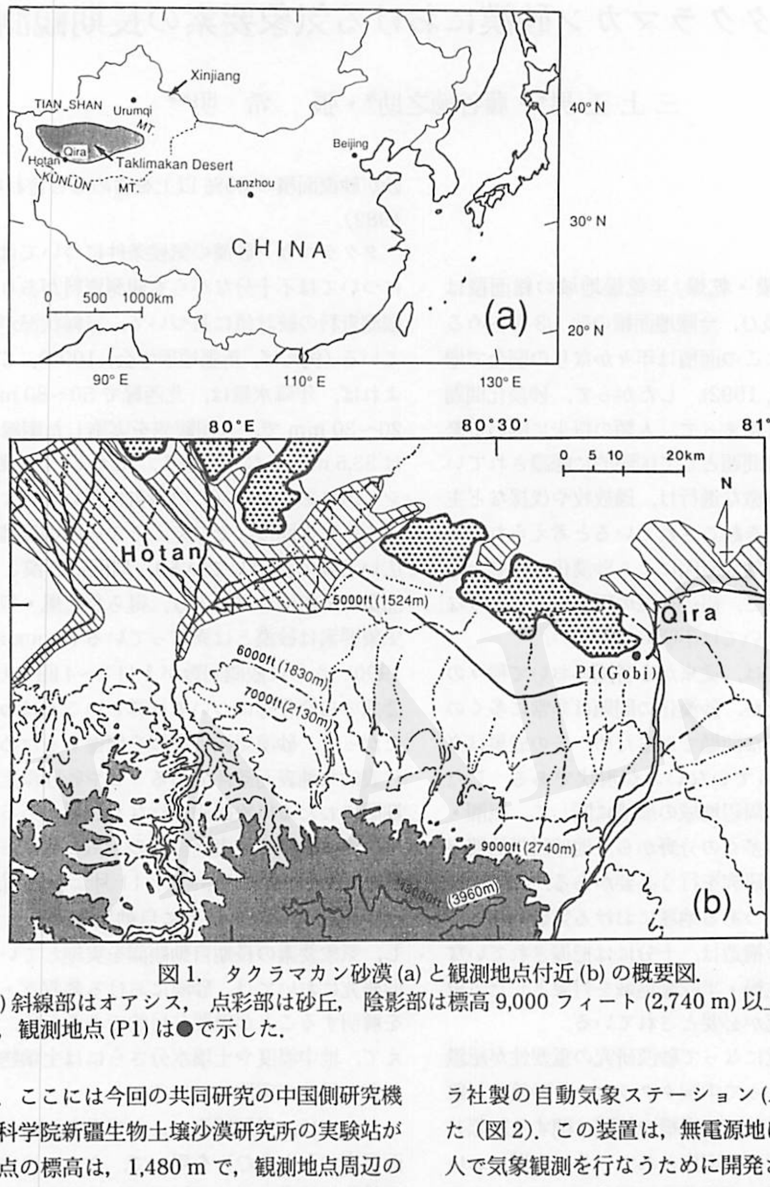

図 1. タクラマカン砂漠 (a) と観測地点付近 (b) の概要図.
図 (b) 斜線部はオアシス, 点彩部は砂丘, 陰影部は標高 9,000 フィート (2,740 m) 以上の山岳部を示す.
また, 観測地点 (P1) は●で示した.

の郊外である. ここには今回の共同研究の中国側研究機関である中国科学院新疆生物土壌沙漠研究所の実験站がある. 観測地点の標高は, 1,480 m で, 観測地点周辺の地表面は図 2 に示すように平坦かつ一様であり, 地表面状態は礫砂漠 (ゴビ) である. 観測地点の南方約 110 km には標高 6,000〜7,500 m の崑崙山脈があり, 観測地点は同山脈とタクラマカン砂漠の中心地帯をつなぐ斜度が 1/1000 程度のほぼ平坦な部分に位置している. 観測地点の北西約 500 m には高さ 30 m 程度の砂丘群が分布し, さらに東方約 500 m には策勒川がある. この川は一時的に流水がみられるワジではなく常に流水が存在している.

2) 観測方法

気象要素の長期連続観測には, ノルウェー・アーンデラ社製の自動気象ステーション (AWS-2700) を使用した (図 2). この装置は, 無電源地において, 長期間・無人で気象観測を行なうために開発されたもので, 輸送・組立・設置・保守のいずれもが, 少人数で比較的簡単にかつ短時間に行なえるようになっている. 電力はマスト上部の太陽電池ユニットから供給される. 図 3 に示すように各センサからの信号は全て, 基部のハウジング内に設置されているデータスキャニングユニットで順次デジタル値 (N 値) に変換され, データストアユニット (DSU) に保存される. さらに DSU に収録された長期データは DSU リーダーを用いて随時パーソナルコンピュータに回収することが出来る.

観測要素は, 風速 (30 分平均値及び測定時間間隔内で 2 秒以上持続した風速の最大値), 風向・気温・相対湿度・全放射量 (上下両方向) ・日射量 (上下両方向) ・

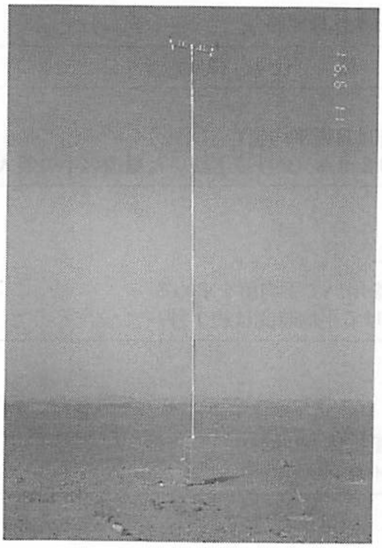

図 2. 策勒郊外ゴビ上に設置した自動気象ステーション.

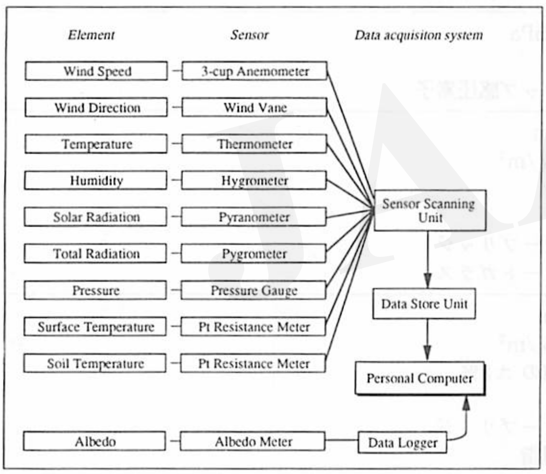

図 3. 観測システム概要図.

気圧・地表面温度・地中温度 (10, 20 cm) の計 11 項目である. 各センサの仕様の概要を表 1 に示す. 測定の時間間隔は 30 分で, 風速以外はいずれも瞬間値が記録される. また観測高度は地上 10 m (気圧は地上 1 m) である. 一方, 地表面温度の測定のために, 測温抵抗体 (直径 8 mm) を, 感部の上側にわずかに砂が被さるようにして深さ約 5 mm の地中に埋設した. 長期観測期間中は, 現地実験站の職員が随時感部の状態をチェックし, 観測が正確に行なわれるように配慮したが, 被っている砂が飛ばされて感部の上側が直接地上に露出する場合も認められた. しかし, 1 年経過後の地中温度センサの埋設深度には変化は見られなかった. また, 地表面の熱収支を評価する場合に必要となるアルベドについては, アルベドメーター (英弘精機 MR-22) を用いて, 研究者が現地滞在中に策勒周辺の各地点において, 適宜測定を実施した.

1991 年 11 月より開始した気象要素の長期観測は現在も継続中であるが, 今回解析を行なったのは, 1991 年 11 月 9 日から 1992 年 10 月 13 日までの 340 日間に得られたデータである.

3. 解析方法

1) センサの較正と精度

砂漠での長期無人観測を実施する場合, 観測に用いる各種センサの特性や精度, あるいは温度依存性などについて事前に把握しておくことは, 得られたデータを用いて砂漠気候の実態を把握し, さらに地表面熱収支を評価するために必要不可欠である. 今回用いるセンサはいずれも長期間の自動観測を目的として設計・製作されており, その耐久性や信頼性については, これまで多くの使用実績によって実証されている. また, 表 1 に示したように, 各センサの精度も通常の気象観測にとっては十分である. しかし, 今回の観測の目的である地表面の熱収支を評価する場合には, 各センサの観測誤差の蓄積が結果の精度に大きく影響すること, 特に日射量・長波放射量の精度が重要であることを考慮し, 現地観測に先立って気象研究所構内で気温, 風速, 湿度, 日射, 全放射, 地温センサについて較正を行った. 自動気象ステーションの測定値は全て N 値と呼ばれるデジタル値 (0～1023) で記録されており, 較正は N 値から各物理量への変換式を求めている.

温度計と地中温度計については, 水温を 5℃ から 45℃ まで段階的に変化させ, 基準温度計の示度と比較した. 得られた各感部の標準誤差は 0.042～0.049℃となり, 本温度計の測定精度 (メーカー資料によれば 0.1℃) 以下となっている.

風速計の較正は, 風洞風速を 1 m/s から 18 m/s まで 1 m/s 毎に段階的に変化させて行なった. メーカー較正値を用いて求めた風速と風洞風速との標準誤差は 0.03～0.07 m/s となり, 風速計の精度±0.2 m/s よりも小さい. さらに, 長期間の使用による風速計の特性の経年変化を調べるために, 風速計を観測環境が厳しい茨城県波崎海岸に設置し, 約 1 年間の無人観測を行なった後, 再度風洞を用いて較正を行なったところ, 風洞風速との標準誤差は 0.04 m/s と以前とほとんど変化がなく, 充分な精度を維持していることが確認された.

風向計は, 粘性率の高いオイルによってダンピングを

表 1. 自動気象ステーションセンサ仕様概略.

測定項目	使用測器	概略仕様
風速	3 杯風速計 (平均) (最大)	起動風速: 0.3～0.5 m/s 測定範囲: 60 m/s 以下 (平均は算術平均値) 精　度: ±2% あるいは±0.2 m/s (2 秒以上続いた風速の中の最大値)
風向	矢羽根式風向計	起動風速: 0.3 m/s 精　度: ±5° 感　部: ポテンシオメーター 注　: ダンピングオイルを用いて平均値を求める (風速 5 m/s における平均時間は約 1 秒)
気温	白金抵抗温度計	測定範囲: −44～49℃ 精　度: 0.1℃ 時定数: 約 6 分 感　部: 白金フィルム測温抵抗体 (2000 Ω) 日射スクリーン: ホワイトナイロン
湿度	感湿繊維湿度計	測定範囲: 5～100% RH 精　度: ±3% RH 時定数: 約 5 分 (室温) 感　部: 応湿伸縮繊維 日射スクリーン: ホワイトナイロン
気圧	半導体気圧計	測定範囲: 770～930 hPa 精　度: ±0.2 hPa 感　部: シリコンチップ感圧素子
日射量	日射計	測定波長: 0.3～2.5 μm 測定範囲: 0～2000 W/m² 精　度: 20 W/m² 時定数: 1 分 感　部: サーミスターブリッジ 風　防: ポリシリケートガラス
全放射量	全放射計	測定波長: 0.3～60 μm 測定範囲: 0～2000 W/m² 精　度: 読みとり値の ±3% 時定数: 1 分 感　部: サーミスターブリッジ 風　防: ルポレン樹脂
地面温度 地中温度	白金抵抗温度計	測定範囲: −44～49℃ 精　度: 0.1℃ 時定数: 約 6 分 感　部: 白金フィルム測温抵抗体 (2000 Ω)

行い，平均値を評価している．この風向計の時定数 τ と風速 U の間に近似的に $U^2=15\ m^2/s$ の関係があることが実験的に確かめられており（萩野谷・藤谷，1989），時定数は風速 5 m/s で 0.6 sec 程度，風速 10 m/s で 0.15 sec 程度となっている．したがって風速の増加と共に，より短周期の風向変動まで追従するが，今回観測を行なった平坦なゴビ上では，粗度長も小さくかつ風速の測定高度も 10 m と高いため，強風時の風向の変動は小さいと考えられ，サンプリング間隔 30 分で測定を行っても特に問題はないと判断した．

気圧計については，比較観測から求めた標準誤差は 0.15 hPa とアーンデラ社の社内較正値による精度（±0.2 hPa）とほぼ同じであり，直線性も良い．

今回使用した湿度計については（メーカーの較正値には 20℃の温度における値しか示されていない）温度依存性があることが報告されており（萩野谷・藤谷，1989），較正値をそのまま使用したときの誤差は相対湿度で最大 10%以上になる可能性がある．しかし，後述するように今回の観測地点の湿度変化は大きいため，目的とする日変化や季節変化を検出することについては特に

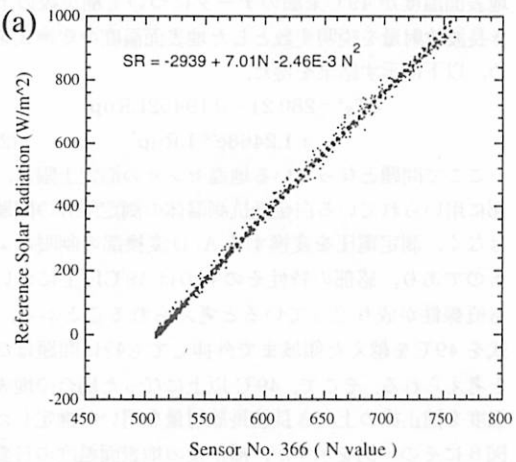

図 4. 日射計 (a) と全放射計 (b) の検定結果例.
図中の式は，N 値から物理量 (W/m²) への変換式を示す.

問題はないと判断した.

日射計と全放射計については事前の較正が重要であることから，研究所内の実験棟屋上に感部を設置し，南に100 m 離れた地点にある気象庁観測部日射計検定室の基準日射計出力及び高層気象台の全放射量測定値と比較した．比較観測は日射計８台と全放射計８台について各々20日間程度実施した（比較に用いたデータ数は日射計が 820～1,005 データ，全放射計が 410～502 データである）．図４に結果の一例を示す（図中に N 値からの較正式を示す）が，基準値と比較観測から求めた較正式による測定値は非常に良く一致している．標準誤差は日射量，全放射量ともに 20 W/m² 程度となっており，この測器のカタログ精度（±20 W/m²）は満たされている．

2) 測定値の補正

観測に際しては，上記の様にその精度確保については細心の注意を払ったが，実際に現地で得られた結果を検討すると，以下に示すような問題点が明らかとなったので，観測値について以下に述べるような補正を行なった．

①日射計のオフセット補正

現地で実際に得られた日射計のデータでは上向き・下向きいずれの日射計にも夜間 10 数 W/m² の値が得られている．日射計については温度依存性はなく，したがって，この値はオフセットと考えられる．そこで，各月毎に夜間の平均値を求め，これを日中の値から減じた値を日射量とした．１年を通じ下向き上向き共に日射量の月毎のオフセット値は正でその変化は小さく，年平均値で下向きが 13.8±2.2 W/m²，上向きが 14.3±3.9 W/m²

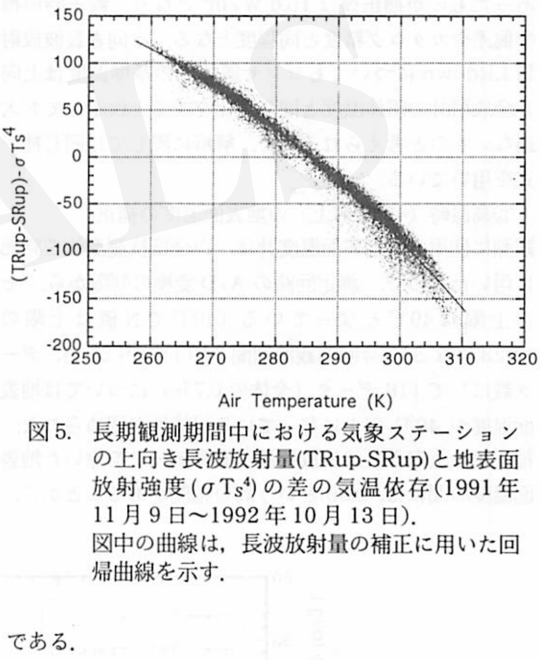

図 5. 長期観測期間中における気象ステーションの上向き長波放射量(TRup-SRup)と地表面放射強度(σT_s^4)の差の気温依存(1991 年 11 月 9 日～1992 年 10 月 13 日).
図中の曲線は，長波放射量の補正に用いた回帰曲線を示す.

である．

②全放射計の温度依存性の補正

今回の観測においては，上向き，下向きの長波放射量 (LRup, LRdown) は，観測される全放射量 (TRdown, TRup) と日射量 (SRdown, SRup) から求めた．

図５に両者の差として求めた，上向き長波放射量と地表面温度から求めた上向き長波放射量との差 LRup-σT_s^4 と気温との関係を示すが，図からも明らかなように，差として得られた長波放射量には気温依存性がある．シリコン製ドームを用いた放射計については，晴天日にドームの加熱によって 20 W/m² 程度の誤差が生じることが報告されている（塩原・浅野，1992）が，今回

の全放射計に用いられているルポレン製ドームの場合，非常に薄く熱容量も小さいため，ドームの加熱による誤差は，シリコン製ドームを用いた放射計よりも小さく本放射計の測定精度 (±20 W/m^2) を考慮すると無視できる程度であると考えられる．今回用いた全放射計は，受感面の温度と匡体内の基準温度の温度差を出力として取り出している．したがって，今回見いだされた長波放射量の気温依存性は，センサ匡体内部の基準温度が周囲の気温の影響を受けて変化したために生じたものと考えられる．そこで，今回の解析では，地上 10 m の気温と σT_S^4 を用いて，上向き長波放射量の気温依存性を補正する式を求めた．得られた補正式を以下に示す．

$$LRup = (TRup\text{-}SRup) + 1715.1 - 17.543Tair + 0.040401Tair^2 \quad (1)$$

解析に使用した全データについて求めた上向き長波放射量と σT_S^4 との差の標準偏差は，補正前は 67.8 W/m^2 であったものが補正後は 15.6 W/m^2 となり，較正時の標準偏差やカタログ精度と同程度となる．下向き長波放射量 LRdown についてもセンサ匡体内の基準温度は上向き全放射計の匡体温度と同じ変化をすると仮定しても大過ないものと考えられるので，解析に際しては同じ補正式を用いている．

③高温時（49℃ 以上）の地表面温度の補正

観測に使用した地表面温度計は，白金抵抗測温体を感部に用いたもので，測定回路の A/D 変換の制限から，その上限は 49℃となっている（49℃でN値は上限の 1,023 になる）．今回の観測期間 340 日の内 23 日，データ数にして 116 データ（全体の 0.7%）については地表面温度が 49℃ 以上になっている可能性が認められた．補正後の上向き長波長放射量と異常データを除いた地表面温度の間には，0.99 という高い相関があることから，地表面温度が 49℃未満のデータについて補正後の上向き長波放射量を説明変数とした地表面温度の変換式を求め，以下に示す結果を得た．

$$\sigma T_S^4 = 280.21 - 0.19452LRup + 1.2468e^{-3}\,LRup^2 \quad (2)$$

ここで問題となっている地温センサの測定上限は，感部に用いられている白金抵抗測温体の測定限界の問題ではなく，測定電圧を変換する A/D 変換部の制限によるものであり，感部の特性そのものは 49℃以上においても直線性が成り立っていると考えられることから，(2) 式を 49℃を越えた領域まで外挿しても特に問題はないと考えられる．そこで，49℃ 以上になった場合の地表面温度を補正後の上向き長波長放射量を用いて推定した．図 6 にその一例を示すが，補正後の地表面温度の日変化の様子は，これまでの裸地面での観測結果と同様の変化の様子を示していることが分かる．

4. 気象要素の年変化と日変化の特徴

1991 年 11 月から 1992 年 10 月までの期間の 30 分毎に得られた各気象要素のデータを用いて，月平均値と時刻別の月平均値を求め，策勒周辺の砂漠気候の基本的特徴について調べた．表 2 に各気象要素の月平均値をまとめて示した．以下，各気象要素についてその特徴を述べる．

①風

月平均風速は 6 月が最大で 5.0 m/s，12 月が最小で 3.1 m/s である．4 月から 8 月にかけては風が強く平均風速は 4.0 m/s 以上を示している（図 7）．一方，冬季の 11，12，1 月は 3.1〜3.2 m/s と年間を通じて最も平均

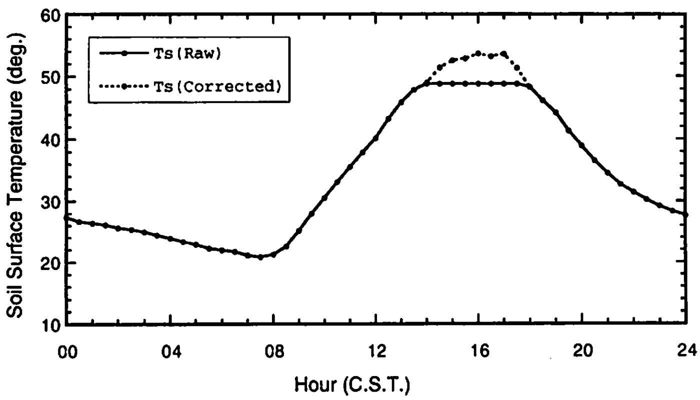

図 6. 気温補正後の上向き長波放射量を説明変数として補正した地表面温度と補正前の地表面温度の時系列（1992 年 7 月 13 日〜15 日）．

表 2. 策勒郊外ゴビ上の各種気象要素と地中温度の月平均値と年平均値（1991 年 11 月～1992 年 10 月）.

Time YYMM	WS m/s	Tair deg.	RH %	ABH g/m³	P hPa	SRdown W/m²	SRup W/m²	LRdown W/m²	LRup W/m²	Rnet W/m²	Tsur deg.	ST10 deg.	ST20 deg.
9111	3.1	3.0	34	2.0	858.2	119	33	261	335	11	4.1	4.7	6.7
9112	3.1	−1.7	59	2.4	855.2	85	26	260	315	5	−0.3	0.7	2.8
9201	3.2	−4.6	70	2.5	855.7	89	25	252	304	12	−3.2	−2.9	−1.2
9202	3.5	0.9	53	2.4	851.5	141	41	265	330	36	2.9	2.5	2.9
9203	3.9	6.9	49	3.6	849.7	130	37	308	364	37	9.6	9.4	9.2
9204	4.2	18.6	20	3.0	848.1	206	60	351	435	62	22.0	20.8	19.2
9205	4.8	20.1	32	5.1	848.3	236	64	371	449	95	24.5	24.1	23.0
9206	5.0	23.9	45	9.1	846.4	258	66	395	475	112	28.8	28.3	27.1
9207	4.4	27.2	43	11.0	845.4	255	68	409	494	103	31.7	30.7	29.6
9208	4.1	25.5	55	12.7	847.2	211	59	409	480	81	29.8	29.4	28.6
9209	3.9	21.3	51	9.5	849.9	179	53	382	447	61	25.0	25.0	25.0
9210	3.8	13.5	60	7.0	855.1	161	50	334	396	49	17.5	17.8	18.8
Average	4.0	13.1	47	5.8	850.5	174	49	335	404	57	16.3	16.1	16.1

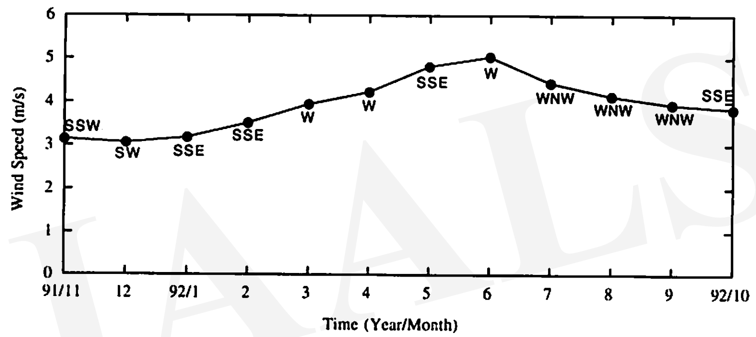

図 7. 策勒郊外ゴビ上の月平均風速（1991 年 11 月～1992 年 10 月）と月別最多風向.

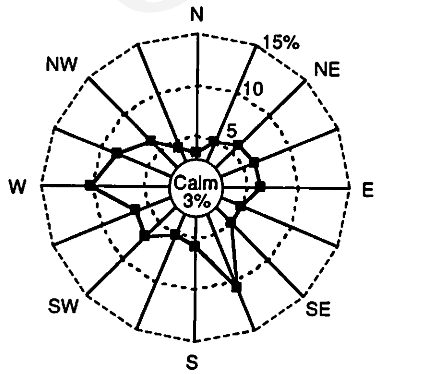

図 8. 策勒郊外ゴビ上の風配図（1991年11月～1992 年 10 月）.

風速が小さい．年間を通じての最大 30 分平均風速は 1992 年 5 月 3 日に記録した 16.0 m/s（風向は西北西），一方最大瞬間風速（30 分間で持続時間 2 sec 以上の風速の最大値）は 1992 年 5 月 27 日の 23.1 m/s（風向は西）である．このような強風が生じた総観場の状況については，現地の天気図などの詳しい気象資料を未入手のため詳細は不明であるが，新疆気象編集委員会 (1992) に掲載されている天気概況の記述によれば，5 月 3 日の強風は，ウラル地方から南下した強い寒気に伴うもので，新疆全域で強風と気温の低下ならびに降雨が観測されている．図 8 に 1991 年 11 月から 1992 年 10 月までの風配図を示すが，観測点の最多風向は南南東，ついで西風となっている．Yoshino (1992) によれば，策勒での主風向は西であるが，今回の調査では南南東と西がほぼ同じ割合で生じている．このような差異が生じた原因を現在のところは明確にすることは出来ないが，後述するようにこの南南東の風は夜間に生じており，一方現地の観測は 1 日 3 回（北京時間で 8, 14, 20 時）であるため，この夜間の風が観測されていないことが一つの可能性として考えられる．これについては今後より詳しい検討が必要である．

砂砂漠の形成と変化には，風による砂の移動，とりわけ強風時の砂の移動が重要であり，特に強風時の風系の特徴は砂砂漠の分布・砂丘の移動方向等と深い関連があると考えられる．長島ほか (1991) は砂砂漠上での観測

結果から風速7 m/s以上では砂面変動が著しくなることを明らかにしている．また，Segal (1990) は数値計算から砂移動が生じる風速を評価し，非常に不安定な成層の場合で4 m/s，安定な成層の場合には5～7 m/sであるという結果を得ている．そこで風速7 m/s以上の風についてその特徴を調べた．月別の強風の発生頻度を見ると，その51.2%は5月から7月に集中している（図9a)．また強風時の風向は西から北西風が全体の74%を占めている(図9b)．吉野(1991) によれば，タリム盆地では4月から6月にかけて風が強く，また強風は5月にしばしば生じ，さらに今回観測を実施した策勒周辺では5月に強い西風が度々生じている．今回の結果は，策勒周辺の風系についてこれまでに得られている気候学的な特徴と同様の特徴を示している．日変化などの風系の特徴については次章で述べる．

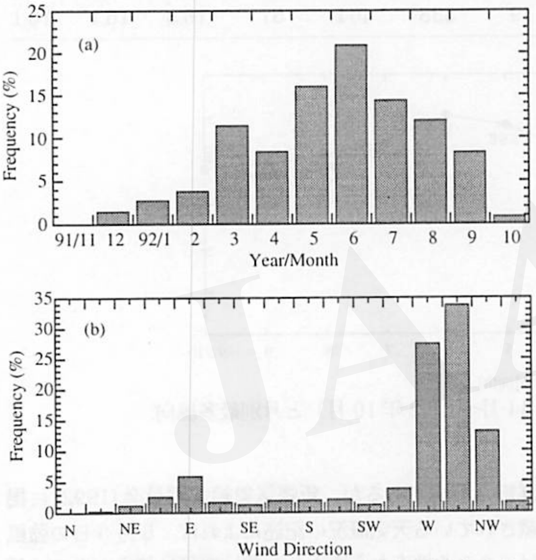

図9．強風（風速7 m/s以上）時の月別頻度分布(a)と風向別頻度分布(b)．縦軸は頻度（単位%）を示す．

②気温

月平均気温は，5月から9月は20℃以上，12月と1月はマイナス（−1.7℃と−4.6℃）を示し，7月が最も高く27.2℃，1月が最も低く−4.6℃であり（表2参照)，年較差は31.8℃にも達する．期間を通じての最高気温は1992年7月20日の37.4℃，最低気温は1993年1月1日の−15.7℃である．年平均気温は13.1℃で，隣接するオアシス和田市内にある和田気象処の平均気温（13.2℃: 新疆地理学会，1993）にほぼ等しい．ただし，和田の気温は地上1.5 mのものであり，一方，策勒の観測は地上10 mであることから，観測点における地上1.5 mの年平均気温は，上述の値よりも多少高くなっていると思われる．

月別に求めた気温の時刻別平均値の時間変化（月別平均日変化）を図10に示すが，時刻別平均値の最大値と最小値の差（ここではこれを平均日較差と呼ぶ）は冬季よりも夏季の方が大きく，1月は6.5℃（晴天日は12℃程度)，7月は9.9℃（晴天日は15℃程度）となっている．Inoue and Mitsuta (1990) による中国北西部黒河流域の砂砂漠における観測例では，平均日較差は2月が最大で7月が最小となっており，今回の結果とは異なった特徴を示している．このような差が生じた原因については，観測地点の地表面状態の差，あるいは周辺の地表面状態の分布の差などが考えられるが，その詳細については今後地表面の熱収支の解析を行なうことによって明らかになるものと考えられる．

③湿度

月平均の相対湿度は4月が最も低く冬季には高くなる傾向を示しているが，絶対湿度 (g/m^3) で見ると，夏季

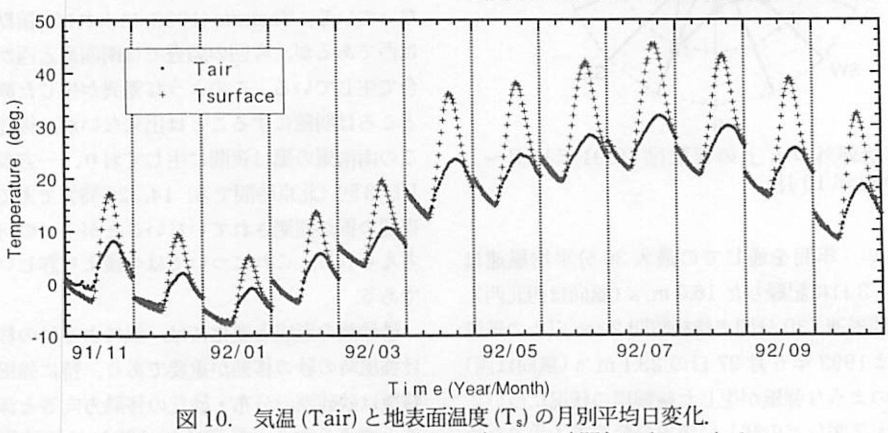

図10．気温 (Tair) と地表面温度 (T_s) の月別平均日変化．時間は北京標準時，横軸の目盛は0時から6時間毎にとってある．

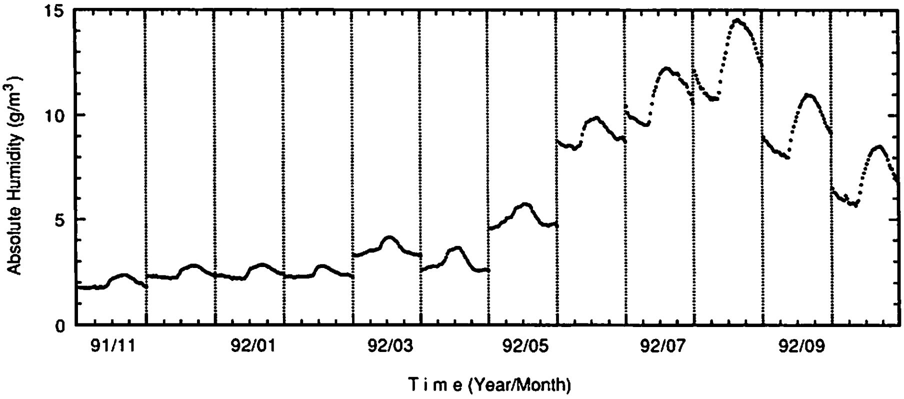

図 11. 絶対湿度（単位 g/m^3）の月別平均日変化.

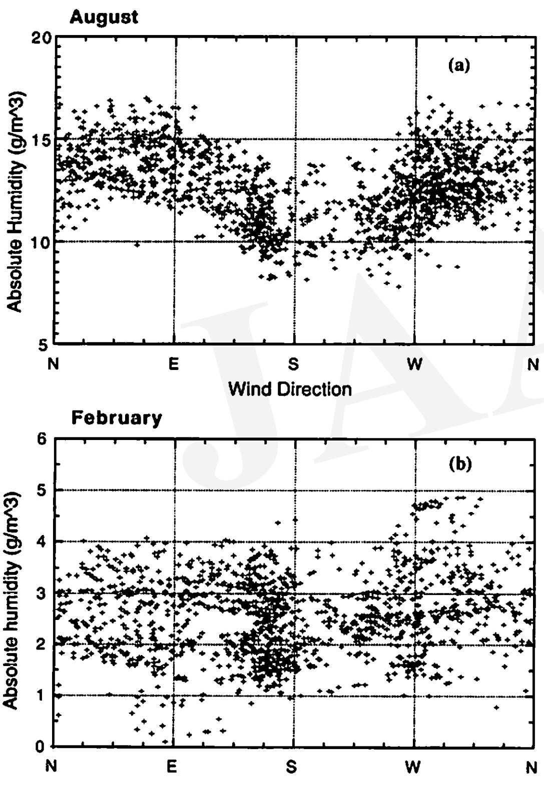

図 12. 絶対湿度の風向別分布.
(a)1992 年 8 月, (b)1992 年 2 月

は水蒸気量が多く冬季は少なくなっており，最高は 8 月の 12.7 g/m^3，最低は 11 月の 2.0 g/m^3 である（表 1 参照）. 11 月から 4 月にかけて月平均絶対湿度は非常に少なく (2.0～3.6 g/m^3)，5 月以降夏季にかけて急激に増大する. 月別に時刻毎に求めた絶対湿度は，いずれの月も夜間は減少し南中前後に最大となっている（図 11）. 平均日較差は冬季の 11 月で 0.6 g/m^3，夏季の 8 月には 3.8 g/m^3 となりいずれの場合も月平均絶対湿度の30%程度になっている. 先に述べた湿度計の測定精度を考慮に入れても，明らかな日変化が認められる. Inoue and Mistuta (1990) による黒河流域のゴビ上における夏季の観測でも，今回の結果と同様に夜間の比湿よりも日中の比湿の方が大きくなるという結果が得られている.

今回の観測地点（ゴビ）の周囲で計測した土壌水分量（含水比）は 0.1～0.3% 程度で，特に地表付近は 0.1% 前後と非常に少さい. 今回のゴビ土壌の場合，0.2% の含水比は体積含水率になおすと約 3 kg/m^3 に相当する. 仮に地表面から深さ 10 cm までの土壌中の全ての水分が日中に蒸発し，高さ 1,000 m の大気下層に水蒸気として拡散するとした場合，含水比が 0.2% の場合には地表面付近の大気中の比湿の増加は 0.6 g/m^3 程度にしかならず，夏季の日中の絶対湿度の増大をゴビの地表面からの蒸発によって説明することは出来ない.

図 12a に夏季（8 月）の絶対湿度の風向別の分布を示すが，夜間の南よりの風の場合には絶対湿度は小さく，一方，北よりの風の場合，絶対湿度は大きくなっている. 観測地点の北北西～北東 10 km と北西 30 km にはオアシスがあり，夏季の日中の絶対湿度の増大は，風上に位置するオアシスからの蒸発散によって生じた水蒸気の移流によるものと考えられる. このような移流は，崑崙山系と砂漠地帯，あるいはオアシスと砂漠地帯の局地循環によって生じていると考えられるが，実際，次章に示すように観測地点の風系には明瞭な時計回りの日変化が見いだされている. 一方，絶対湿度の顕著な日変化が見られない冬季（2 月）については，図 12b に示すようにその風向依存性は見られない. 策勒県の有効灌漑面積は 2 万 ha に及ぶ（吉野ほか，1993）が，冬季は耕作のための灌漑は行なわれず，オアシス内の植生も減少する. さらに，冬季は降水量も夏季に比べて少なく（1991 年 10 月～1992 年 4 月降水量 4.2 mm，1992 年 5 月～9 月降

水量 14.2 mm)，崑崙山脈からの河川流量も少ないためオアシス全体からの蒸発散が少なく，絶対湿度の風向依存性が顕著に現れないものと考えられる．

④地表面温度と地中温度

月平均地表面温度と地中温度 (10 cm，20 cm) は図 13 に示すように，いずれも 1 月に最低値，7 月に最高値を記録している．月平均地表面温度は 12 月から 1 月にかけて 0℃ 以下となり，一方 7 月には 31.7℃ の最高値を示している．また，月平均地表面温度は常に気温よりも 1℃ から 5℃ 程度高くなっている．年平均値は，地表面温度が 16.3℃，10 cm と 20 cm の地中温度が共に 16.1℃である．年較差は，地表面，10 cm，20 cm でそれぞれ 34.9℃，33.6℃，30.8℃ なっており（表 2 参照)，地上 10 m の気温の年較差 31.8℃と大きな差はない．

月別に時刻毎に求めた地面温度の日変化を図 10 に示すが，11 月と 12 月を除き，夜間は気温と地表面温度との間に大きな差はない．11 月と 12 月の夜間は，地表面温度が気温よりも顕著な場合で 2℃ 程度低い接地逆転を示している．日中の気温傾度は 7 月には最大 10℃ 程度に達する．また，地表面温度の月別の平均日較差は，1 月が 12.6℃，7 月が 23.5℃となっており，前章で述べた地上 10 m の気温の平均日較差の約 2 倍に達する．

⑤日射量，放射量

全天日射量は，12 月が最も小さく，6 月に最大値を示す．月別時刻別に平均した全天日射量の日変化を図 14 に示すが，12 月の南中時の平均日射量が 380 W/m² 程度，6 月は 810 W/m² 程度である．夏季晴天日の南中時には，1000 W/m² を超える日（6 月 12，18 日，26～29 日，7 月 4，6 日）もある．この時の日射量と計算によって求めた大気上端日射量との比は 0.8 前後にもなるが，大気下層の水蒸気量が少ない事と大気層の厚さが薄い事（地上気圧 850 hPa 程度）がその理由として考えられる．

下向き日射量＋下向き長波放射量－上向き短波放射量－上向き長波放射量で定義される正味放射量の月積算平均は，表 2 に示すように 12 月が最も小さい値を示し，ほぼ 0 に近くなる．一方，最大値は 6 月で 100 W/m² 以上に達する．さらに図 15 に月別の平均日変化を示すが，

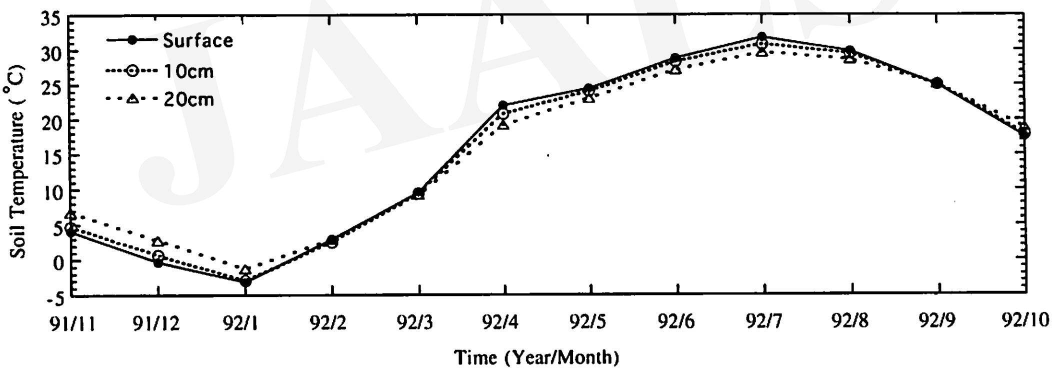

図 13. ゴビの地表面温度 (T_s) と地中温度 (10 m，20 cm) の月平均値の時系列（1991 年 11 月～1992 年 10 月).

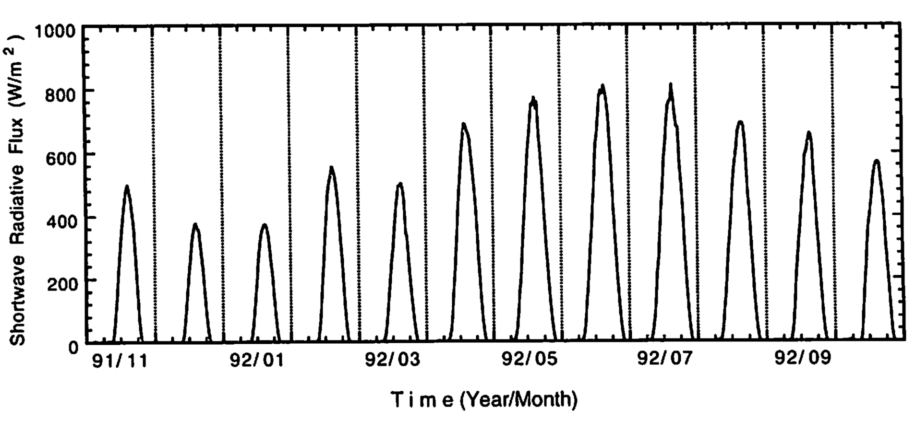

図 14. 下向き全天日射量（単位 W/m²) の月別平均日変化.

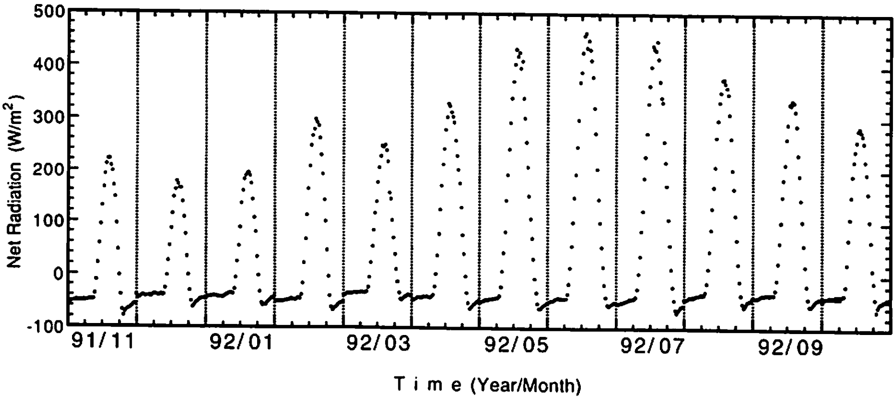

図 15. 正味放射量 (SRdown＋LRdown－SRup－LRup) の月別平均日変化.

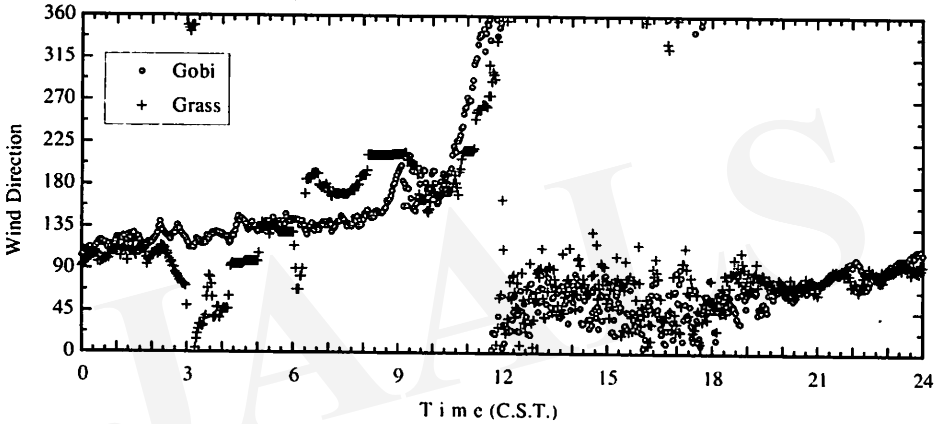

図 16. 集中観測時（1993 年 10 月 17 日）のゴビと草地上における風向日変化.
測定時間間隔は 2 分毎.

最も大きい 6 月の南中時の正味放射量でもおよそ 480 W/m² 程度である．この値は中緯度の他の地表面条件での値（裸地面，650 W/m²: Novak and Black, 1985; 草地，550 W/m²: Ripley and Redmann, 1976; 落葉広葉樹林，800 W/m²: 三上，1992）などよりも小さい値を示している．ゴビの場合は後述するように地表面アルベドが大きいことと，土壌水分が極端に少ないために地表面温度が上昇し，地表面からの上向き長波放射が大きいためにこのような結果になるものと考えられる．夜間の正味放射量については，季節変化は特に見られず，いずれの月も日没直後に－60 W/m² 程度の上向きの値を示し，その後次第に減少して日の出前に－40 W/m² 程度になっており，サヘルの裸地での観測例（Wallace *et al.*, 1990）とほぼ同様の結果となっている．

5. 策勒周縁ゴビ上の風系の特徴

策勒周辺の風向の頻度分布については，今回得られた 1 年間の風配図（図 8）では南南東と西の風が卓越しており，これは長島ほか (1991) の観測結果とも一致している．このうち西風は，4 章で述べたように，5 月から 7 月に集中して発生する強風によるものである．一方，南南東の風には季節依存性はなく，1 年を通じて出現している．現地調査期間中に，測定間隔 2 分で実施した集中観測時の，ゴビの風向の日変化を図 16 に示すが，これによると明瞭な時計回りの風向の日変化が認められる．1 年間の風向の日変化を求めるため，3 時間毎に区分した時間帯毎の卓越風向の時間変化を図 17 に示す．これによれば，21 時から 06 時にかけての夜間は卓越風向が南南東になっており，一方，日中は時間と共に西から北東へと時計回りに卓越風向が変化している．すなわち風配図に見られる南南東の卓越風向は，風系の日変化に伴って生じる夜間の風であることが分かる．

今回観測を行なった策勒郊外のゴビは，土壌水分量が極めて少ないため，先にも述べたように地表面温度などの日変化は顕著である．さらに，観測地点は，南方崑崙

山系（高度 6,000 m 程度）と北方に広がる砂漠地帯との間の緩やかな斜面上に位置している．このため熱的な成因による局地循環が発達しやすい条件を備えている．

図 18 に示した風速の月別平均日変化によれば，8 月から 9 月は夜間よりも日中の風速が強いが，秋季から冬季にかけての期間（1991 年 11 月～1992 年 2 月，1992 年 10 月）は日中の風速は弱く，夜間の方が日中よりも風速が強い．オアシスの植生が減少する（すなわち砂漠とオアシスの温度の差が顕著でなくなる）秋季から冬季においても夜間 4 m/s 程度の風が持続すること，1 年を通じて夜間の風向が崑崙山脈の位置する南からであることを考慮すると，今回見いだされた風向の日変化は，砂漠地帯と南方の崑崙山系間の局地的循環によって生じている可能性が考えられる．中国国内においてもこのような局地循環についてはいくつかの観測例が報告されているが（例えば，ZHANG and LIN，1992），今回の場合水平スケールは 100 km 以上とこれらの事例よりも大きく，循環の構造や成因については今後詳しく調べる必要がある．

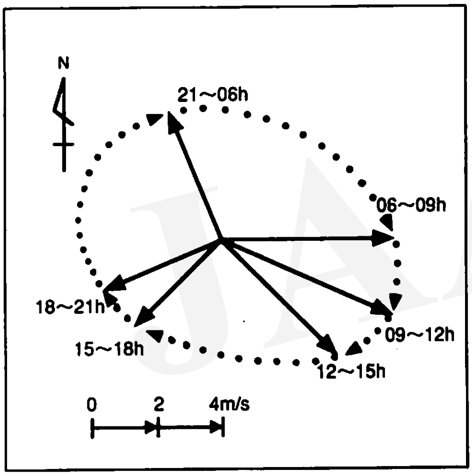

図 17．策勒郊外ゴビ上の3時間毎の主風向風速図（1991 年 11 月～1992 年 10 月）．図中の点線は，風向の時間変化を示す．

6. 地表面のアルベド

アルベドは地表面熱収支に関する最も基本的なパラメーターであるが，砂漠における観測はこれまであまり報告されていない．現地調査期間中，アルベドメーター（上下 2 方向に水平に取り付けた 2 つの日射計感部から得られる下向き全天日射量と地表面反射日射量の比を測定する）を用いて，オアシス周縁の疎な草地，大麦畑（発芽期），蘆葦群落（草丈約 50 cm），砂砂漠，ゴビの各地表面のアルベドを測定した．測定位置，標高，天候及び観測時間を表 3 に示す．アルベドは，アルベドメーター出力の 10 分間積算値から求めた．いずれの地点においても図 19 に示すように南中時にアルベドが最小となる顕著な日変化を示し，太陽高度角依存性が認められた．アルベドメーターによる測定は，日の出直後と日没前の時間帯については行っていないが，積算日射量は南中時前後の日射量が大部分を占めるため，例えば今回のゴビの場合で日の出から日没までの積算日射量の約 75% に相当する量を測定していることになる．また，1 日の積算日射量から計算したアルベド（8：30～18：30 P.S.T.）はアルベドメーターの測定時間帯の積算値から求めたアルベド（12：00～17：30 P.S.T.）と比較して 2.4% の差にしかならなず（0.314 と 0.306，ゴビの自動気象ステーションのデータで評価した場合），アルベドメーターの測定精度±3% に比較して無視できる程度である．したがって，ここでは観測時間について日射量を積算して求めたアルベドを日積算平均値と呼ぶことにする．表 3 に示すように，観測時刻や天候については各地点とも大差

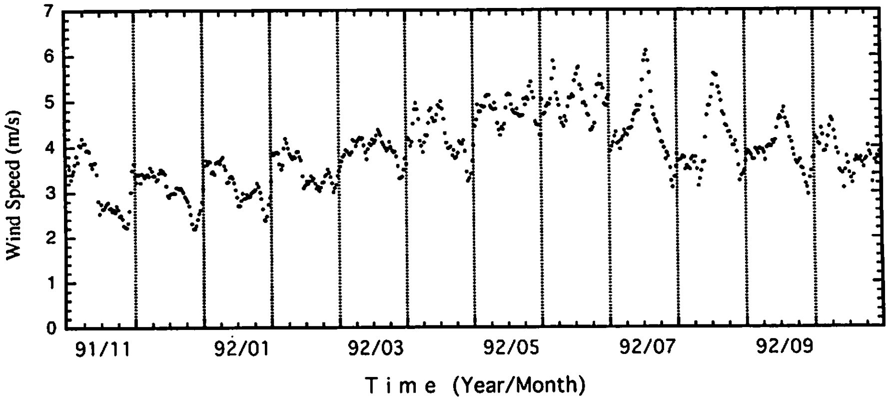

図 18．策勒郊外ゴビ上の風速の月別平均日変化．

表 3. アルベド測定点の地表面条件，位置，海抜高度，観測時間及び天気.

Location	Position	Height	Period (B.S.T.)	Weather Condition
Grass	10 m southeast of P2	1,370 m	11:40 to 19:30 Oct. 16 1993	Clear
Lu Wei field	100 m northeast of G.H.	1,370 m	10:20 to 19:30 Oct. 17 1993	Clear
Barley field	150 m north of G.H.	1,370 m	09:40 to 19:20 Oct. 18 1993	Fine→Clear
Grass	30 m east of P2	1,370 m	09:30 to 18:20 Oct. 19 1993	Fine
Sand dune	N36°55′50″ E80°46′11″	1,510 m	12:06 Oct. 20 to 18:20 Oct. 21 1993	Clear→Fine
Gobi	N36°55′36″ E80°47′09″	1,480 m	11:30 to 17:30 Oct. 22 1992	Clear

P2 は北緯 37°00′57″，東経 80°43′46″ の地点，G.H. は北緯 37°00′58″，東経 80°43′52″の地点を示す.

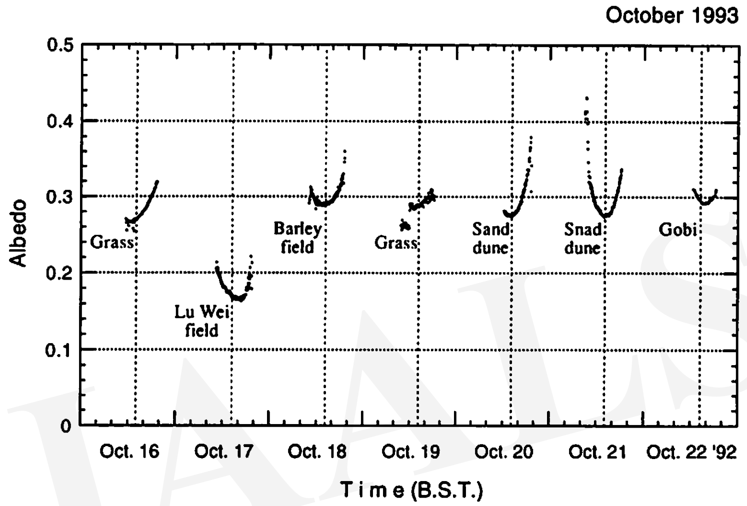

図 19. 策勒郊外各地点におけるアルベドの時系列.
ゴビ以外は 1993 年 10 月，ゴビは 1992 年 10 月の観測. 図中の点線は，南中時間を示す.

はないので，各地点で得られた結果を比較すると，アルベドの日積算平均値は，大きい方から順に，ゴビ (0.30)，大麦畑 (0.30)，砂砂漠 (0.29)，草地 (0.28)，蘆葦群落 (0.18) となっている. このうち大麦畑は発芽期にあたり地表面の大部分は砂で覆われており，また草地は駱駝刺 (*Alhagi pseudoalhagi*) や蘆葦 (*Pharagmites communis*) を中心とした植被率が 30% 程の疎な草地であるため，蘆葦群落を除く 4 地点のアルベドはほぼ同じ値 (0.3 前後) を示し，森林 (0.15 前後) や草地 (0.2 前後) よりも大きな値となっている. また，ゴビで得られた積算平均値と，気象ステーションの同時期 (1992 年 10 月) の月積算日射量から求めた同時間帯 (北京時間からの時差を補正した現地の地方時間で 9 時 20 分から 14 時 50 分) のアルベドの積算平均値 (0.31) はほぼ一致しており，気象ステーションの日射計の測定結果は妥当なものであると考えられる.

7. おわりに

中国タクラマカン砂漠南部のオアシス策勒郊外のゴビに自動気象ステーションを設置し，1991 年 11 月 9 日から 1992 年 10 月 13 日までの約 1 年間にわたって気象要素と地中温度の長期自動観測を行なった. 得られた資料を解析した結果，以下のことが明らかとなった.

①月平均風速は 6 月が最大で 5.0 m/s，12 月が最小で 3.1 m/s である. 4 月から 8 月にかけては風が強く平均風速は 4.0 m/s 以上を示している. 一方，冬季の 11，12，1 月は 3.1 m/s〜3.2 m/s と年間を通じて最も平均風速が小さい.

②ゴビ上の風向は，南南東と西の風が卓越している. 南南東の風は夜間に卓越しており，一方西風は 5 月から 7 月に集中して発生する強風に伴うものである.

③7 m/s 以上の強風についてその月別の強風の発生頻度を見ると，51.2% は 5 月から 7 月に集中している. ま

た強風時の風向は西から北西風が全体の74%を占めている.

④風向の頻度分布は南南東と西の風が卓越している. 1年間の風向の日変化を求めると明瞭な時計回りの風系の日変化が認められる. 21時から06時にかけての夜間は卓越風向が南南東になっており, 一方, 日中は時間と共に西風から北東風へと時計回りに卓越風向が変化している. これは, 策勒南方の崑崙山系と北方の砂漠地帯の間に局地循環が存在していることを強く示唆している.

⑤月平均気温は7月が最も高く27.2℃, 1月が最も低く−4.6℃であり, 年較差は31.8℃にも達する. 年平均気温は13.1℃で, 隣接するオアシス和田の年平均気温(13.2℃)にほぼ等しい.

⑥月平均の相対湿度は4月が最も低く冬季には高くなる傾向を示しているが, 絶対湿度で見ると, 夏季は水蒸気量が多く冬季は少なくなっている. 11月から4月にかけて月平均絶対湿度は非常に少なく(2.0〜3.6 g/m^3), 5月以降夏季にかけて急激に増大する. 月別, 時刻別に求めた絶対湿度は, いずれの月も夜間は減少し南中時前後に最大となっていて, とりわけ夏季は顕著である. このような夏季の日中の絶対湿度の増大は, 風上に位置するオアシスからの蒸発散によって生じた水蒸気の移流によるものと考えられる.

⑦月平均地表面温度と地中温度(10 cm, 20 cm)はいずれも1月に最低値, 7月に最高値を記録している. 地表面温度は12月から1月にかけて0℃以下となっている.

⑧全天日射量は, 12月が最も小さく, 6月に最大値を示す. 12月の南中時の平均日射量が380 W/m^{2}程度, 6月は810 W/m^{2}程度である. 夏季晴天時の南中時には, 1000W/m^{2}を超える日もある.

⑨正味放射量の月積算平均は, 12月が最も小さい値を示し, ほぼ0に近くなる. 一方, 最大値は6月で100 W/m^{2}以上に達する.

⑩オアシス周縁の疎な草地, 大麦畑(発芽期), 蘆葦群落(草丈約50 cm), 砂砂漠, ゴビの各地表面のアルベドは, いずれの地点においても南中時に最小となる顕著な日変化を示した. 日積算平均値は, ゴビ(0.30), 大麦畑(0.30), 砂砂漠(0.29), 草地(0.28), 蘆葦群落(0.18)の順となっている.

今回の報告においては, 現地観測で得られた資料に基づいて, 砂漠における基本的な気象要素の日変化, 年変化など基礎的な解析結果のみを示した. 現在, 得られた資料の解析を継続しており, 今後は, 砂漠における気象の特徴をより詳細に把握するために, 地表面の熱収支の評価, 崑崙山系と砂漠地帯の間の局地循環の構造や成因についても解明する.

謝　辞

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日射計の較正に際しては, 気象庁日射計検定室廣瀬保雄検定官に, また全放射計の較正に際しては, 気象庁高層気象台観測第三課の職員各位に, 施設やデータの提供等で協力していただいた. この場を借りてお礼申し上げます.

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Long-term Meteorological Observation in Taklimakan Desert, China

Masao MIKAMI*, Tokunosuke FUJITANI* and Ximing ZHANG**

For investigating the desertification processes of arid lands, long-term meteorological observation has been performed in Taklimakan Desert in Xinjiang, China since 1991. The automatic weather station was settled over gobi desert at the southern edge of the desert near the small oasis, Qira. Meteorological elements at a height of 10 m and soil temperature were measured every 30 minutes since November 1991. Almost one year of data were analyzed and the obtained preliminary results are summarized as follows:

(1) The monthly mean wind speed shows a maximum in June (5.0 m/s) and a minimum in December (3.1 m/s).
(2) There are two prevailing wind directions: westerlies and southsoutheasterlies. Southsoutheasterlies arise during nighttime. Westerlies are accompanied with strong winds which appear during May, June and July.
(3) Diurnal clockwise wind course is found throughout the year. This suggests the existence of mountain-plain circulation between Kunlun Mountains and the desert area.
(4) Air temperature and soil temperatures show minimum in January, and maximum in July. The annual mean and annual range of air temperature are 13.1℃ and 31.8℃ respectively.
(5) Absolute humidity increases at daytime in summer season. The reason for this daytime increase may be caused by the water vapor advection from oasis located in the windward side of the observational site.
(6) The monthly means of net radiation shows a maximum in June (over 100 W/m^2) and a minimum in December (nearly 0 W/m^2).

Key Words: Taklimakan Desert, Local circulation, Desert climate

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特集　第4回沙漠工学講演会講演要旨集

日本沙漠学会沙漠工学研究分科会*

概　要

本稿は，日本沙漠学会沙漠工学研究分科会主催で行われた第4回講演会の講演内容を，プログラム，質疑応答とともにまとめたものである．年に1度の講演会も既に4回目となったが，今回もその要旨，議論を本学会誌を通じて学会員の方に広くお伝え出来ることはたいへん光栄であると考えている．今回予定では，吉川氏の講演が予定されていたが，氏のよんどころない事情により小島の講演に振り替えられた．誌面を借りお詫び申し上げる次第である．氏には改めて1995年7月に開催予定の沙漠工学研究会において後講演頂く予定としているが，講演要旨については講演Vとして今回の要旨集に併せて掲載させて頂いた．なお，第1回～第3回までの記録は過去の学会誌をご参照されたい．

本研究分科会も活動開始後既に3年以上を経過し，役員他の制度も整い，ますます活発化しつつあると自負している．マングローブ体験ツアー，「沙漠物語」（森北出版）も好評とお聞きしている．さらに，沙漠物語に続く啓蒙書の刊行等も検討中である．特に本年（1995年）には，本沙漠学会主催の国際会議「Desert Technology III」が富士本栖湖ホテルで10月15日～20日まで開催されることとなっており，是非ご参加ご協力を頂ければ幸いである．　　（文責：小島紀徳）

プログラム

1994年10月18日(火)，於：成蹊学園（武蔵野市）
総合司会：清水建設(株)　大塚義之（以下敬称略）
記　　録：(株)荏原製作所　結城邦之（分科会副会長）
13:00～開会挨拶：理化学研究所　遠藤　勲（分科会会長）
13:10～講演I.　：アラビア半島南東部の水循環：千葉大学理学部　佐倉保夫
（司会：清水建設(株)　井伊博之）
14:00～講演II.　：エネルギーと環境からみた沙漠工学：成蹊大学工学部　小島紀徳
（司会：前田建設(株)　佐竹　潔）
14:40～総合討論I., 休憩
15:25～講演III.：持続可能な開発の事例研究—サスティナブル・デベロップメント・グリーンフィールド—：電力中央研究所　新田義孝
（司会：清水建設(株)　高木史人）
16:05～講演IV.：世界の沙漠化と日本の環境保護法の課題：弁護士，生物多様性防衛ネットワーク事務局長　井口　博
（司会：理化学研究所　遠藤　勲）
（講演V.：黄砂と日本海側山岳地帯の降雪：気象庁気象研究所　吉川友章）
16:55～総合討論II.
17:20～閉会挨拶・Desert Technology IIIの案内：成蹊大学　小島紀徳（分科会副会長）

* 〒113 東京都文京区本駒込2-28-8　理化学研究所駒込分所　日本沙漠学会内　Tel. 03-3947-7708

Special Report
Proceedings of Fourth Symposium on Arid Land Technology

The Japanese Research Group for Arid Land Technology* (REAL Tech)

This special report is the proceedings of the fourth symposium of The Japanese Research Group for Arid Land Technology held at Seikei University, Musashino, Tokyo, on October 18, 1994.

The first lecture was given by Prof. Yasuo SAKURA, Chiba University, on "Water Cycle in South-Eastern Part of Arabian Peninsula".

The second lecture was a general topic given by Prof. Toshinori KOJIMA, Seikei University, the head of The Water Research Division of our group, on "Desert Technology: Energy and Environmental Points of View".

The third lecture was given by Dr. Yositaka NITTA, Central Research Institute of Electric Power Industry, The Head of Biological Research Division of our group, on "A Possible Sustainable Development Greenfield".

The last lecture was given by Mr. Hiroshi IGUCHI, a lawyer, on "The Concept of the Environmental Protection Law and Prevention of Desertification".

In the present Proceedings, one extra paper entitled "Yellow Sand and Snowfall in the Mountain Area of the Japan Sea Side" by Dr. Tomoaki YOSHIKAWA, is also included, which had been scheduled in the Symposium but unfortunately was canceled. This lecture will be given in the next summer meeting of REAL Tech in 1995.

* c/o The Japanese Association for Arid Land Studies. The Institute of Physical and Chemical Research, 2-28-8 Honkomagome, Bunkyo-ku, Tokyo, 113 Japan.

沙漠研究　4, 121-127 (1995)
Journal of Arid Land Studies

I.　アラビア半島南東部の水循環

佐　倉　保　夫*

I.　Water Cycle in South-Eastern Part of Arabian Peninsula

Yasuo SAKURA*

1. はじめに

アラビア半島南東部には，ペルシャ湾に面したアラブ首長国連邦 (UAE) とアラビア海に面したオマーン王国がある．気候は，基本的には高温・乾燥な沙漠気候を示すが，沿岸部では夏季には湿度も高い．年平均気温は25℃から30℃で，年間の降水量は沿岸部で 90 mm，山地部で 140 mm から 160 mm 程度である．アブダビ，ドバイ，マスカットなどの海岸部に位置する大きな都市では，生活用水として海水を脱塩蒸留した水を使用している．これは火力発電所に併設されており，廃ガスが原料であるためコストはそれほど高くはないということである．しかし，内陸部では，生活用水，農業用水などに地下水が広く利用されている．

UAE では緑化政策の推進により，アブダビ市内はも

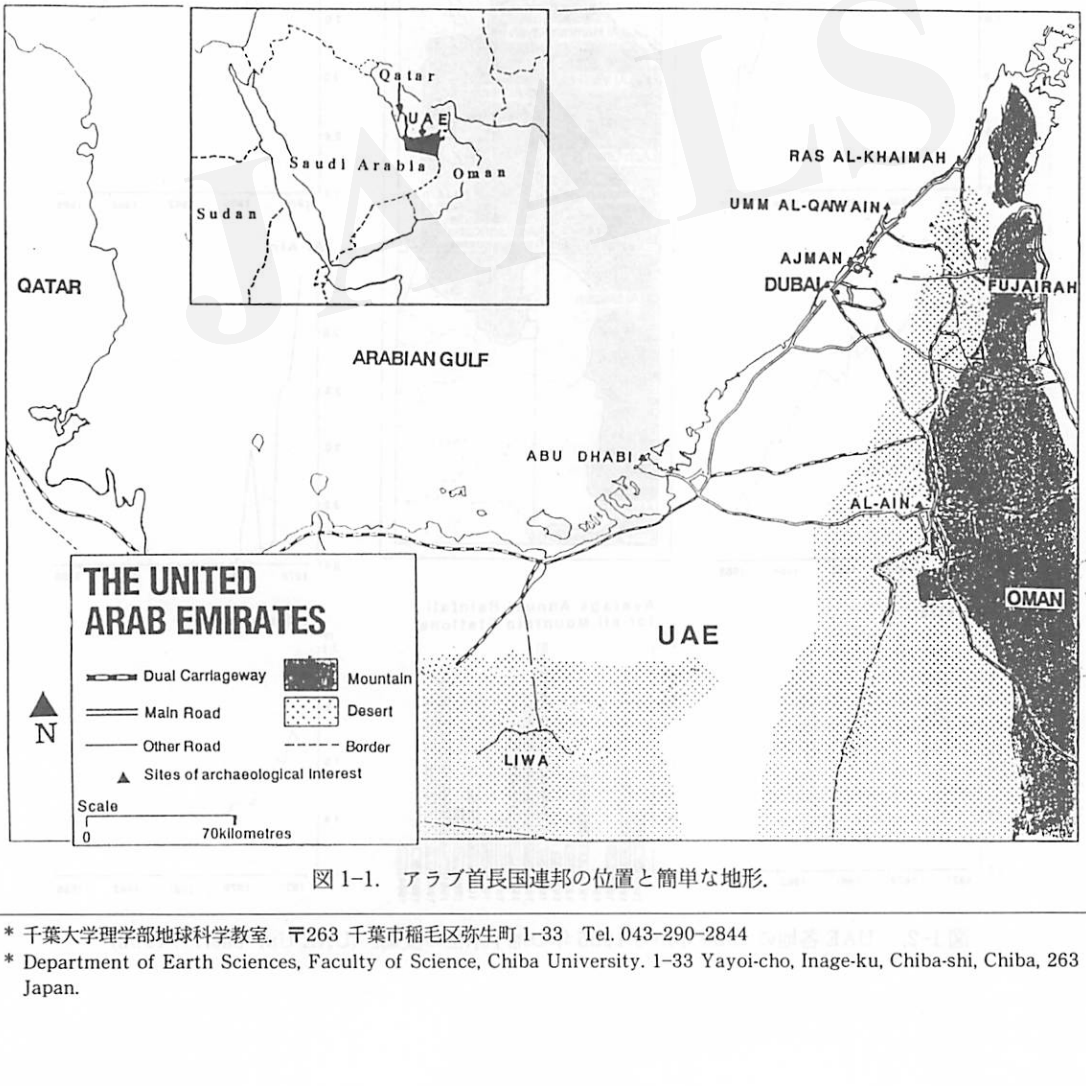

図 1-1.　アラブ首長国連邦の位置と簡単な地形.

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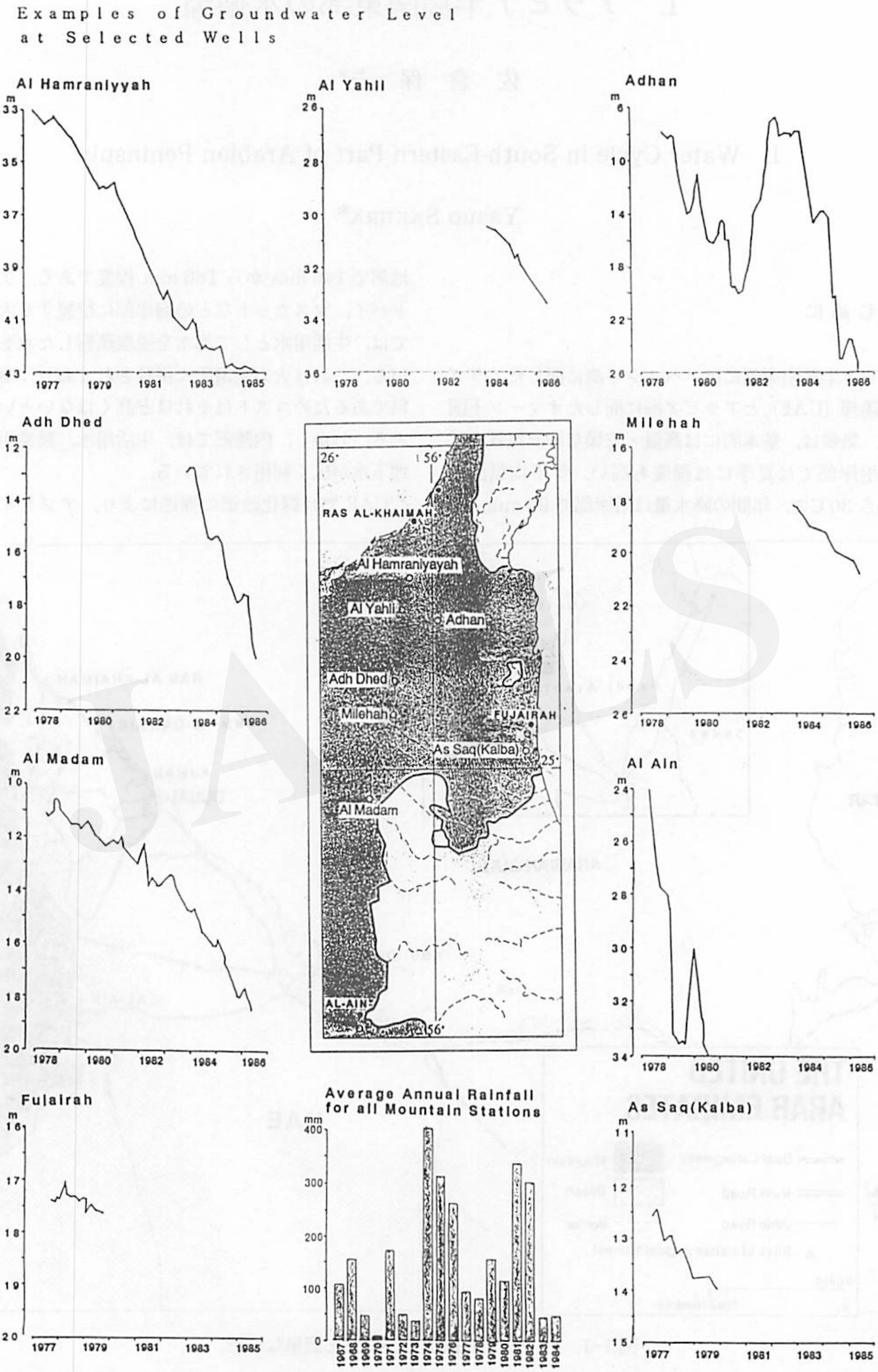

図 1-2. UAE 各地の 1969 年から 1985 年の地下水位の変動. (UAE University, 1993)

とよりアブダビーアライン間 150 km の幹線道路沿いには幅 200 m におよぶ緑地帯が形成されている．そのほか人口増加や農業活動の増大のため，UAE だけではなくオマーンにおいても脱塩蒸留水の供給がない内陸部の都市や農業地帯では地下水の水位低下は深刻な問題となっている．年間降水量が 100 mm 程度の乾燥地では，地下水の持続的な利用のために地下水涵養機構を把握することが重要である．筆者らは，1994 年度から乾燥地域の水循環とともに地下水の涵養機構を明らかにすることを目的とした研究を計画している．また 1993 年 9 月には 2 週間ほど予察的な現地調査を行ったので，UAE 大学が出版したナショナル・アトラス (UAE University, 1993) を例としてこの地域の水循環の考え方と水利用の実態とをあわせて報告する．

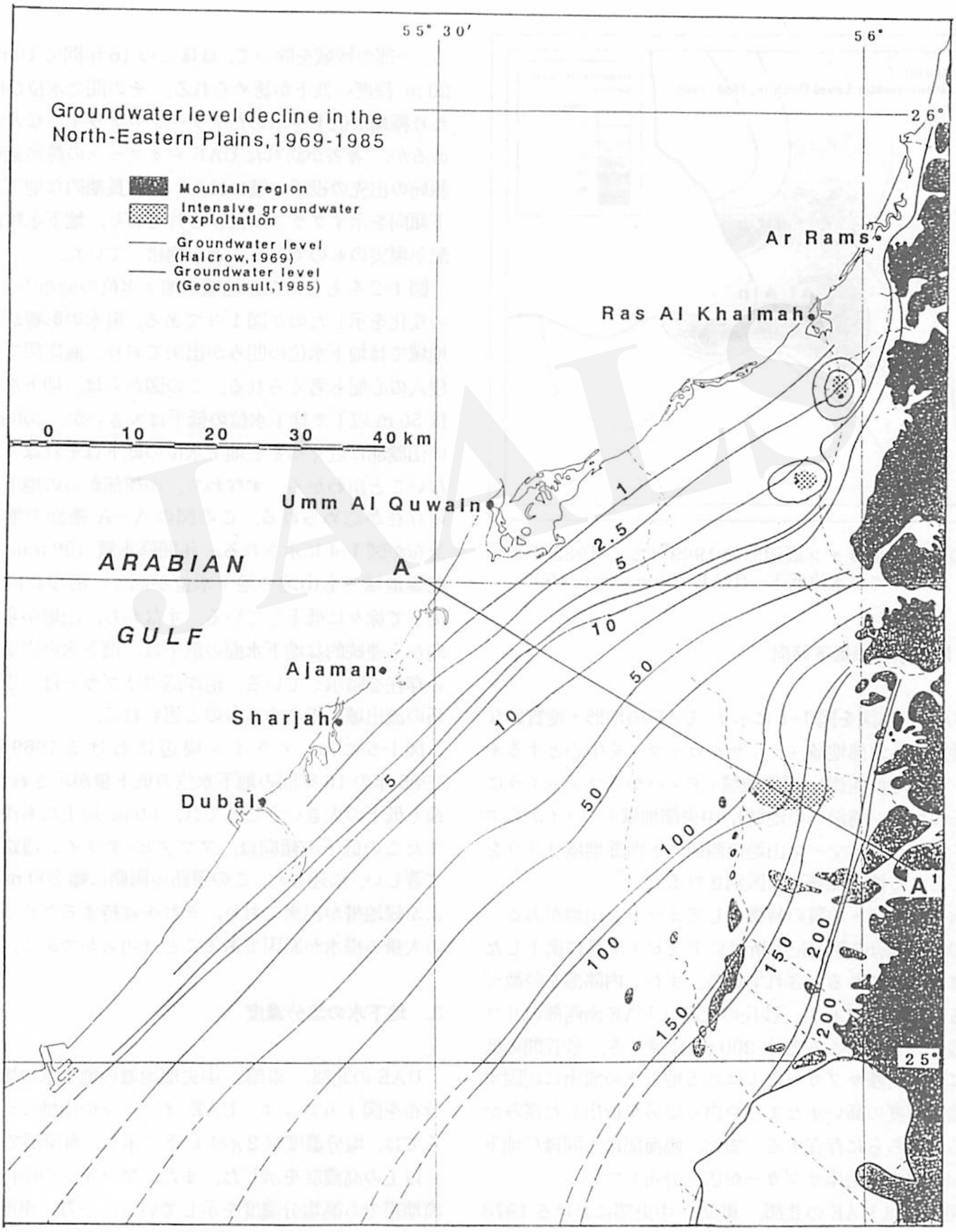

図 1–3. UAE 北西部の 1969 年と 1985 年の地下水位. (UAE University, 1993)

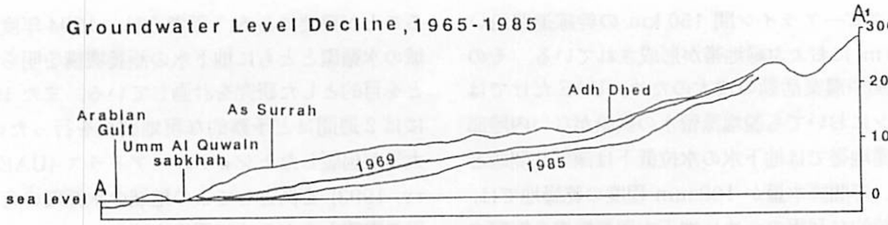

図 1-4. 図 1-3 の A—A' 断面の地下水位. (UAE University, 1993)

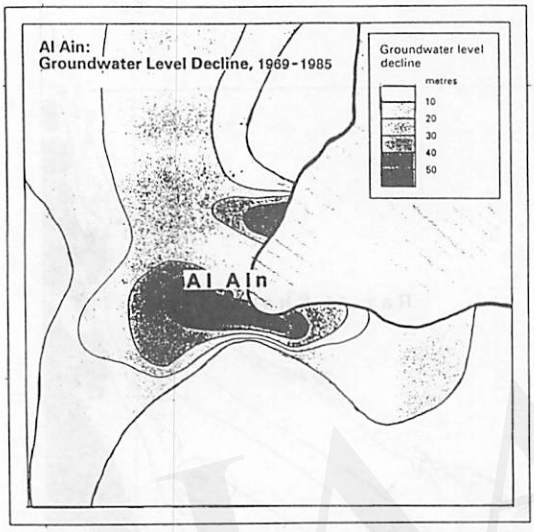

図 1-5. アライン周辺での 1969 年から 1985 年までの水位低下. (UAE University, 1993).

2. 地下水位の低下傾向

UAE の地図を図 1-1 に示す. UAE の地形・地質的な条件から, 北部地域（ラッサルカイマーを中心とするオマーン山地の西側), 東部地域（ディバからフジャイラに至るオマーン湾沿いの地域), 中央部地域（ドバイからアラインに至るオマーン山地の西側）と西部地域（リワを中心とする沙漠地域）に区別される.

大きな地形・地質の特徴としてオマーン山地がある. 2,000 万年前の第三紀中新世にアラビア半島に衝上した海洋性地殻であるとされている. また, 内陸部を特徴づけるのは沙漠である. 砂丘の比高は UAE 南西部のリワ周辺で大きいところでは 200 m に達する. 砂丘間の低地には, 内陸サブカーとよばれる地下水の流出に起因する塩分濃度の高い水たまりや白く塩分が析出した窪みがあちらこちらに存在する. また, 臨海部にも同様な地下水が流出する沿岸サブカーが広く分布している.

図 1-2 は UAE の北部, 東部, 中央部における 1978 年から 1986 年までの地下水位の低下傾向を示している. 一部の地域を除いて, ほぼこの 16 年間で 10 m から 20 m 程度の低下が認められる. その間で水位が回復したり極端な低下を示したアダーンやアラインなどの例もあるが, 著者が訪れた UAE やオマーンの農漁業省水資源局の出先の役所の壁には, いつも長期的な地下水位低下傾向を示すグラフが掲げられており, 地下水枯渇の心配が現実のものであることを物語っていた.

図 1-2 をもとにこの地域の地下水位の分布の 16 年間の変化を示したのが図 1-3 である. 揚水の影響が大きい地域では地下水位の凹みが出来ており, 海岸部では海水侵入の心配も考えられる. この図からは, 地下水位が海抜 50 m 以下で地下水位の低下は大きいが, 200 m 程度の山麓部に近くなると地下水位の低下はそれほど大きくないことがわかる. すなわち, 山麓部からの地下水涵養の存在が認められる. この図の A—A' 断面の地下水位分布が図 1-4 に示される. 年間降水量 100 mm 程度の乾燥地域でも山地で地下水位が高く, 海岸に向かうに従って徐々に低下している. すなわち, 山地から海岸に向かう連続的な地下水面の低下は, 地下水の広域流動系の存在を暗示している. 沿岸部のサブカーは, 広域流動系の流出域に相当するものと思われる.

図 1-5 には, アライン周辺における 1969 年から 1985 年の 16 年間の地下水位の低下量が示されている. 最も低下の大きいところでは, 50 m 以上にも達する. またこの低下の傾向は, アブダビ-アライン道路に沿って著しい. 前述した, この道路の両側に幅 200 m にもおよぶ緑地帯が出来ており, それを維持するための地下水の大量の揚水が原因であることは明らかである.

3. 地下水の塩分濃度

UAE の北部, 東部, 中央部地域の地下水の塩分濃度分布を図 1-6 に示す. UAE-オマーンの山地に近いところでは, 塩分濃度が 2 g/l 以下を示し, 海岸部では 5 g/l 以上の高濃度を示した. また, アラインの南西部の沙漠地帯でも高塩分濃度を示している. 一方, 東部地域ではフジャイラなど一部の地域を除いて海岸部まで, 低塩

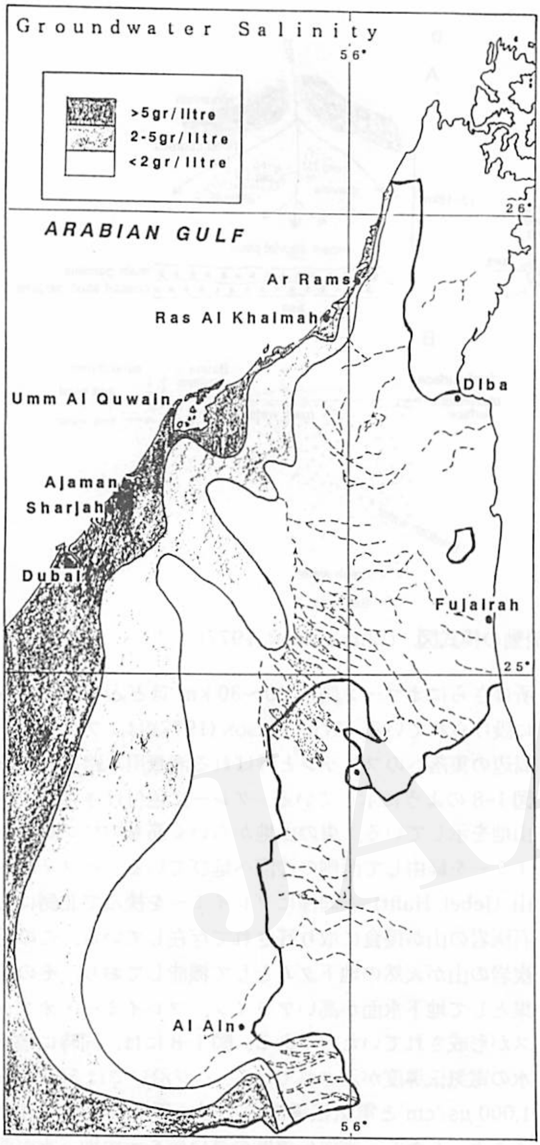

図1-6. UAE北部，東部，中央部の地下水の塩分濃度分布．(UAE University, 1993)

分濃度の地下水が認められる．山地の近くに分布する低塩分濃度の地下水は，滞留時間も短く淡水として利用可能な水である．5 g/1 以上の濃度になると，滞留時間も長く，なつめ椰子など特殊な植物以外では生育が阻害されるようになる．

4. 乾燥地の水循環

Willkinson (1977) は，アラビア半島南東部における典型的な二つの地域の地下水流動の様子を図 1-7 のように示した．図 1-7a にはリワの沙漠からアブダビに至る地域を，図 1-7b には UAE の東部地域の南方で地形的に類似するオマーンのバチナコーストにおける山地から東方の海岸に至る地域を示している．前者では，砂丘が地下水の涵養域であり，小さな砂丘間低地やリワ周辺の構造的な低地あるいは砂丘間の窪地である内陸サブカーが流出域である．砂丘下の宙水として存在する地下水がさらに砂丘の基盤を透過して，ペルシャ湾岸沿いの塩分が集積する沿岸サブカーやさらにはアブダビ西方の海底にも流出していたことが報告されている．後者では，オマーン山地山麓の山地から供給された堆積物で形成された扇状地の降雨や雨期のワジにおける洪水流が地下水の涵養源であり，塩淡水境界が形成される海岸部が流出域となる．

中央部地域のオマーン山地西側で砂丘と接する地域は，Willkinson (1977) の模式図には示されていないが，図 1-7b の A で海を砂丘に置き換え，南北の山地列に対して南西から北東へ砂丘列が迫っていると考えればよい．雨期の洪水流は山地からワジを経由して，砂丘間の低地である内陸サブカーへ流れる．従って，山麓部やワジが涵養域で，砂丘間低地では蒸発により流出すると考えられている．

5. 持続可能な地下水利用の将来

アライン周辺のワジには，100 m メッシュの格子点で深度 100 m から 150 m ほどの揚水用の井戸群が多数分布しているところがある．それらの井戸から揚水された水が，50 m 四方の大きなプールに集められている様子をみて，驚きと同時に感動したことを覚えている．北部地域のワジの中でもアラインから北の沙漠地帯でも，多数の揚水井群が存在する．

沙漠地域でも 10 年に 1 度程度の洪水が発生している．アライン周辺のワジの源流部はオマーンの山地であるが，そこでは 1 年中表流水をみることが出来る．通常は 1 月から 3 月の雨期に 100 mm を超すような豪雨が発生すると，山地の表流水が溢れ出しワジを流下して洪水を発生させるのではないかと推測される．そのような洪水が海や沙漠に素早く流れ込むのを阻止し，地下水の強化に役立てようとして考えられたのが涵養ダムである．数 km にわたる長大なものまで，無数に分布している．しかし，その効果がどれほど有効だったのかという評価は充分になされていないようであった．

UAE のアラインはオマーンのブレイミーと接しており，かつては一つのオアシスを利用する同じ集落であった．現在でも行き来は自由であり，オマーンの通関事務

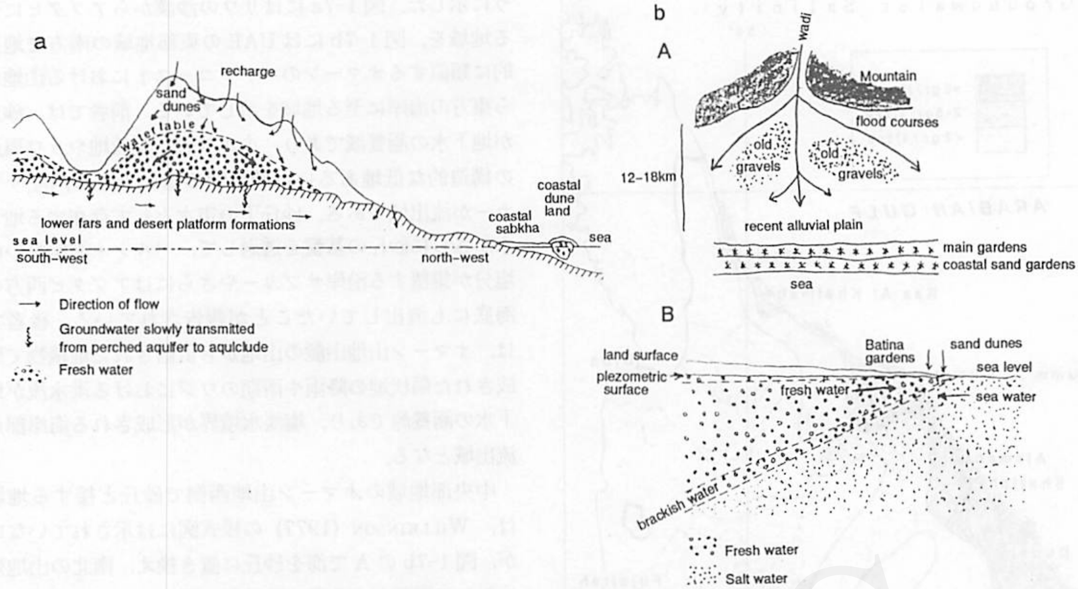

図 1–7. アラビア半島南東部の地下水流動の模式図. (Willkinson, 1977)

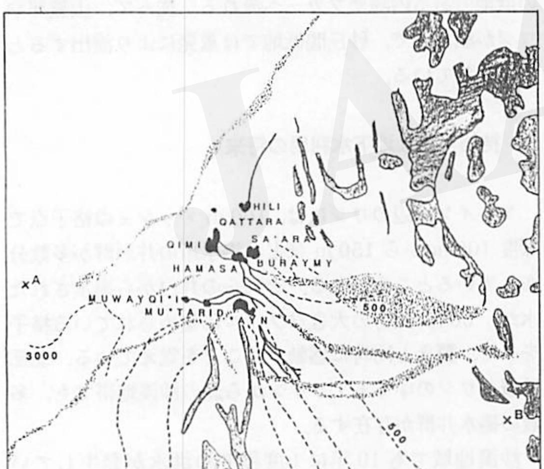

図1–8. ブレイミー，アラインのオアシスの灌漑水路. (Willkinson, 1977)

所はさらにオマーン側に 20〜30 km ほど入ったところに設けられている. Willkinson (1977) は，ブレイミー周辺の集落へのファラジと呼ばれる灌漑用水路の分布を図 1–8 のように示している. グレーに色付けされたのが山地を示している. 東の山地からいく筋ものワジがブレイミーを経由して西側の沙漠へ延びている. ハフィット山 (Jebel Hafit) と同様にブレイミーを挟んで北側にも石灰岩の山が侵食に取り残されて存在している. この石炭岩の山が天然の地下ダムとして機能しており，その結果として地下水面が高いアライン，ブレイミー・オアシスが形成されていたのである. 図 1–8 には，同時に地下水の電気伝導度が示されている. ワジ沿いでは 500 から 1,000 μs/cm と電気伝導度の小さい新鮮な水が存在すること，しかし，電気伝導度の高い値を示す地下水が西側の沙漠地帯やハフィット山を取り囲むように循環から取り残されたように存在していることなどが明らかである.

以上のことを総合すると，今後も従来と同様な地下水利用が継続されるようならば，地下水位の低下と塩分の高濃度化が続き，やがては量的にも質的にも地下水利用が困難となることは明らかである. それらを防止するためには，山地山麓から沙漠や海に至る間に地下ダムを建設し，山側で無効放流をくい止めてより多くの良い水質の水利用が行えるようにすることが積極的な方法であろう. いずれにしても乾燥地域においては，水収支を念頭に置き，地下ダムで地下水位のモニターを行いながら涵養に見合った水利用を行うことが必要である.

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Key Words: Water cycle, Arabian Peninsula, Groundwater, Salinity

質疑応答

Q: 小島（成蹊大学）
水がコースタル・サブカー（海岸の低湿地）に出てくる年月のオーダ，この計測方法，およびそのフロー（流れ）がどのような形であるのか，その考え方について知りたい．また水温による判断は可能であるのか．

A: オマーンではカナダ人が放射性同位体（^{3}H: トリチウム）による年代計測を行っている．その結果，北部の東海岸では出てくるまでに数年から10年かかっているようである．南部の沙漠では，深いところから来るものは3万年から数万年かかっている．これは炭素(^{14}C) の同位体で判断している．UAEのアブダビ周辺の海岸の地下水は数万年以上のオーダだと思われる．このような同位体で計測した結果を基に，大雑把なシミュレーションをすることができる．インターナルサブカー（内陸部の砂丘間にあるサブカー）では，流動からみれば数年から数十年であろう．水温から見るのは難しいが，長時間かかると温度が上ったり，含有物の濃度が濃くなると思うがデータが少ないので判断できていない．

Q: 安部（筑波大学）
塩水楔の話だと思うが，地下水を垂直に汲み上げ水位の低下があった後，地下水が山側か海側，両方から集まって来て，なおかつ塩濃度が高まるメカニズムについてはどうなっているのか．

A: このメカニズムについては，まだこれからの研究である．UAEではアラインの北側になるが，水位，水質（塩分濃度）の計測を予定している．今までのデータから分布を予測して，シミュレーションをし，そのメカニズム等を検討しようとしている．

Q: 高宮（草炭研究会）
10年で地下水の水位変動はどれくらいあるのか．

A: 今までのデータで見ると8年で10m低下，16年で50m低下があり，また1年で20m低下の例もある．

Q: 高宮
その帯水層の厚さはわかっているのか．

A: 基盤までの深さは，深くても100mくらいと推測している．水がなくなる心配はない．使えばまた周囲の山側からの地下水の供給があり，水位はそれほど急には低下しないであろう．

沙漠研究 4, 129-132 (1995)
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II. エネルギーと環境からみた沙漠工学

小 島 紀 徳*

II. Desert Technology: Energy and Environmental Points of View

Toshinori KOJIMA*

1. はじめに

沙漠化をはじめとする地球環境問題は，他の地球環境問題やエネルギー問題とは切っても切れない関係にある．環境問題に対する対策を考えると，そこには必ずといってエネルギーが関与する．これらの環境問題は人的な関与が引き起こしたものといってよく，その意味でエネルギーを含め，人的活動を含めて考える必要がある．沙漠化も同様である．自然の範囲内での気候変動，あるいは異常気象によるものは，むしろ自然災害であり，環境問題ではない．また，超異常気象があるとするならこれも人為的と考えるべきだろう．

沙漠化の原因としては，種々の人為的影響が考えられるがその一つに薪などのエネルギー採取の問題が上げられる．これは原因としてのエネルギーとの関わりである．全地球規模の環境問題として二酸化炭素問題が上げられる．これはほとんどエネルギー問題と同意と考えてよいが，その対策技術のひとつとして沙漠の緑化による炭素固定が上げられる．一方で，沙漠は日本などの高緯度，多雨地域と比べて太陽の恵みが多く，太陽光直接発電，太陽熱利用，温度差，風力はじめ様々な自然エネルギー生産の場として考えることが将来必要となろう。そしてさらにこれらのエネルギーを環境改変に適用することこそ，沙漠工学のひとつの役割と考えられる．地球環境の問題は，「何が地球に優しいか？」すら明確になってはいないといって良いだろう．沙漠化防止のために，二酸化炭素を放出しながら貴重な化石エネルギーを大量に使用するなら，そのこと自身は沙漠には優しくとも，地球には決して優しくはない．本講演では，何が地球に優しいかを，様々な視点，特にエネルギーに関連させながら，著者の見解を述べる．

2. 沙漠化と薪の利用

森林破壊あるいは沙漠化の一因である薪の利用について議論しよう．サヘル地域等での沙漠化の原因として若木等を薪として利用することが上げられる．もちろんその背景には人口増加と自然の気候変動があるが，人類の過剰な利用が沙漠化を促進していることは間違いが無い．まず第一の視点は，このエネルギーが何に使われるかである．途上国ではもちろん全使用エネルギー量は先進国に比べ小さい上に，図 2-1 に示すようにその大部分が調理用エネルギーに用いられる．（注：薪年間 1 トンを 570 ワットと計算しているが，これは薪の発熱量を数千 kcal/kg とし，その熱を夜昼かまわずずっと使っているとして平均した値．電気ストーブをずっとつけっぱなしにしたと思えばよい．）そして一人当りの調理用エネルギー使用量は先進国に比べ非常に大きい．すなわちその利用効率は著しく低く，非効率的であるといわざるを得ない．緑のサヘル等でもその活動の一環としてかまどの熱効率改善に取り組んでいるようである．

それでは薪を石炭などの化石燃料におきかえることはどうだろう．経済的な問題はあるが，出来ないことではないだろう．その薪の採取が，もしそのまま育成するならば樹木となるであろう若木からなされているならば，石炭に変えることでも沙漠化は防げる．しかし，それは，もし熱効率の改善がなされないままであるならば，後述の二酸化炭素の排出増につながるであろうし，また硫黄酸化物などの問題も生じるかも知れず，望ましいとは思えない．

薪を使った場合，エネルギーの利用効率が低い一番の理由は，固体の非効率的燃焼にあるのだろう．固体の場合，燃えはじめるまでに時間がかかり，調理が終わってもすぐに火は消えない．一方，灯油にしろガスにしろ止めたければコックをひねるだけである．小さな炉でもよいからガス化炉があり，ガスを貯めるタンクがあれば便利になり，エネルギー効率も大幅に改善されるのではないかと期待される．仮に薪を使うにしてもガス化すればその使用量は大幅に削減出来よう．

沙漠で得られるもうひとつのエネルギー源は太陽エネルギーである．太陽熱による熱湯供給あるいは凸レン

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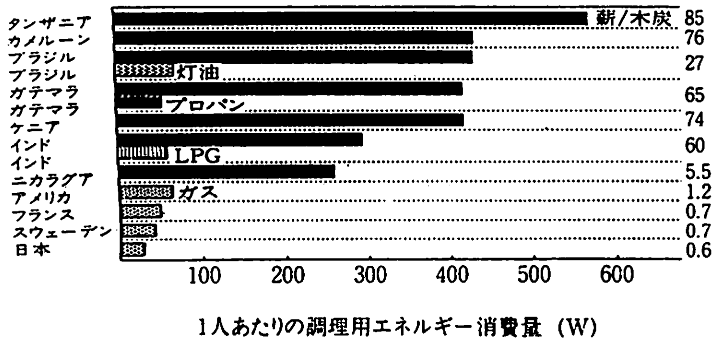

注：年間1tの薪を燃焼したときのエネルギーは平均 570 W

図 2-1. 発展途上国における1人当りのエネルギーの消費量.
右の数値は調理用エネルギーの比率，%.（カーメン，1993; 小島，1994）

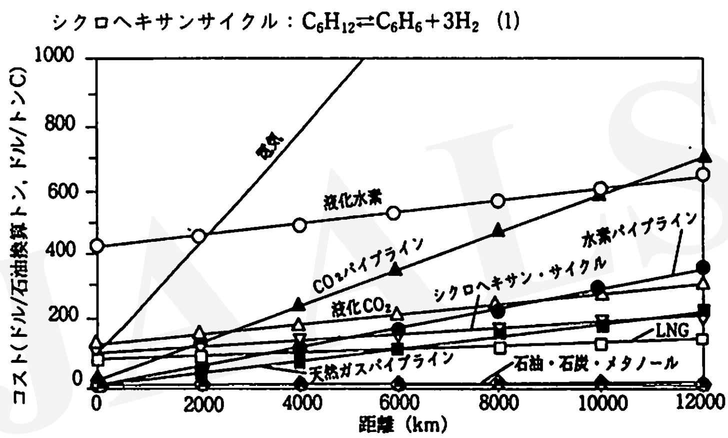

図 2-2. 各種エネルギーの長距離輸送コスト.（藤井，1993; 小島，1994）

ズ，凹面鏡集光による炊事用熱源の供給等の簡易的なエネルギー供給手段が考えられる．アルミ箔を箱に貼り，太陽光を反射により集めるだけの物でも，2lのお湯が50分で沸くという（カーメン，1993）．目的に応じたエネルギー利用が大事だろう．

3. 沙漠での自然エネルギーによる発電とその輸送

上述のように沙漠は雨もほとんど降らず，雲も少なく，いつでも太陽が降り注いでいる．そのうえ，日本より緯度が低い地域では，その力も強い．同じ太陽電池でも，あるいは太陽熱利用でも日本の数倍近い働きが期待できる．

風も強い．牛山（1993）によれば，夜には風も強く，太陽の補完的役割も期待できるという．もちろん調理用の他，造水，揚水，送水に用いることが出来る．直接太陽熱によりポンプを駆動する，ソーラーポンプシステム（日本太陽エネルギー学会，1985），風力ポンプ（牛山，1993）なども，沙漠での利用が期待される．

しかし，これからの世界のエネルギー供給を考えると，このような自然エネルギーを利用しない手はない．海洋エネルギーもあるが，それよりも陸上というだけで実現には近いような気がする．まずは発電だろう．風力については，日本は小規模なものがあるだけだが，カリフォルニアの沙漠の丘陵地では，風車がずらりと並んだ光景がみられるという．太陽電池については，実用化にはまだまだ問題もあるが，効率は年々増大しつつあり，価格も下がりつつある（稲葉ほか，1993）．

しかし，最も大きな問題はエネルギー輸送の問題である．エネルギーの輸送コストを図 2-2（藤井，1993; 小島，1994）に示す．これから，石炭，石油といった化石燃料が実は非常に運びやすいことに気がつく．しかし，電気を直接輸送するとすれば，これは膨大なコストとなる．電気分解により水素を造り，パイプラインで運ぶと

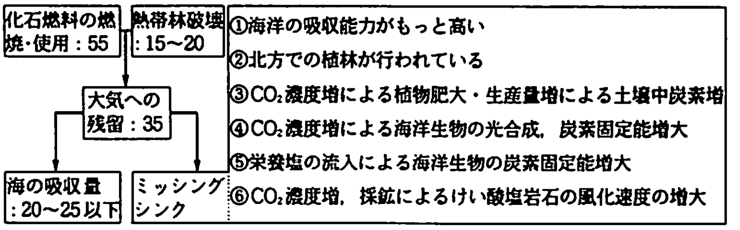

図 2-3. 人類が関与したことによる非定常的炭素移動（億 t/ 年）．
1978〜1988 年平均．（小島，1994）

しても日本は非常に遠い．エネルギー多消費型産業，例えば鉄，アルミ産業を沙漠に置き，製品を運ぶとすれば，エネルギーを運んだことになる．沙漠に産油国があるとするなら，重質油の軽質化，脱硫のための水素をまずは太陽電池で作ってみたい．重質な油を輸入する代わりに軽質化した油を輸入すれば，その一部が太陽エネルギーの缶詰となる．もう少し大規模にやるのなら，石炭を沙漠に運び，それを電気分解で作った水素で液化することも出来るだろう．中国には石炭も沙漠もある．液化をするには最適な場所である．ただ問題は液化残渣がでること．そのためには液化の効率を上げるという技術開発が必要である．

しかし，拙著（安部ほか，1994）にも書いたように，最もエネルギーを消費し，そしてエネルギーをかけずに運べる「人間」をエネルギーの豊富な沙漠に運ぶ．それが「沙漠に人が住む日」であり，そのための工学として沙漠工学がある．と最近思い始めている．あまりにSF的すぎるだろうか．

4. 地球温暖化問題，二酸化炭素問題，そして沙漠緑化

地球温暖化問題において二酸化炭素の寄与は最も大きいといわれている．しかし，二酸化炭素はエネルギーを生産したから生じたガスであり，残念ながらこれを工学的に“固定する”ことは原理的に不可能である．そのほかの対策，すなわち二酸化炭素を回収し，これを海洋や地中に隔離することも，できればやりたくない．なぜならそのためにまた余計なエネルギーを大量に使わざるを得ないからである．

さて，地球規模の炭素循環は，図2-3（小島，1994）に示すように化石燃料の使用に伴い炭素換算で年間約55 億トン（1979〜1988 平均）が放出され，そして大気にはこのうちの 65% 弱の二酸化炭素（炭素換算で年間35 億トン程度，1979〜1988 平均）が蓄積される．

一方で，一般的には熱帯林破壊，沙漠化により二酸化炭素は 15〜20 億トン—C 程度放出されていると考えられている．この数字の信頼性は乏しいものの，実は非常に大きい意味を秘めている．すなわち，前述の大気中への残留二酸化炭素量，35 億トン程度の半分にもなっているのである．熱帯林破壊，沙漠化さえ防止すれば，大気への残留が半分となり，さらには従来の熱帯林破壊とほぼ同一速度で逆に植林を進めるとすれば，二酸化炭素問題は解決し得るともみなし得るのである．

最近こそ化石燃料の寄与は大きいが，歴史的にみればむしろ森林の破壊により放出された二酸化炭素の方が蓄積量としてはずっと多い．そしてその用途は，農牧畜あるいは鉄，煉瓦生産等のエネルギー多消費プロセスに用いられたとされている．沙漠を緑化することは，環境破壊では決してない．沙漠は沙漠であるべきとの議論は，少なくとも人為的に出来た沙漠には当てはまらない．元の森林に戻すべきだ．

それでは問題は何か．もちろん水である．淡水製造は非常にエネルギーを要する．塩水，海水が手に入ったとしてもである．一所懸命エネルギーをかけて水をつくり，その水で森林をつくり，その森林から得られる生産物を燃やしても，かけたエネルギーは回収できない．多重効用缶を使っても，省エネルギープロセスである膜を使ってもである（松村・小島，1991）．

結局のところ現状ではこれらの効率を上げる工夫とともに，むしろ節水などにより水の有効利用を図り，必要水量を減らすことに重点を置くことになる（小島，1991）．水の用途と，必要な水質との関係を明らかにすることが必要である．日本ガス協会 (1994) では，沙漠地に大規模に雨を降らせることまで考えている．夢のような話であるが，近い未来に最も現実味のある技術なのかも知れない．

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Key Words: Energy, Environment, Desertification, CO_2 problem

質疑応答

Q: 新田（電力中研）
植林の大切さはわかるが，世界的にはどのようにすれば実現しうるか.

A: 個人的には環境税などによりもっとエネルギー価値を高くしていいと思う．エネルギー資源量には限りがある．一方，自然エネルギー，特にソーラエネルギーあるいは高速増殖炉，核融合などの原子力エネルギー（もちろん安全である必要はあるが）がコマーシャルになるまで何年かかるであろうか．太陽等の自然エネルギー開発のためや植林に環境税を使えばよい．あるいは植林をすれば環境税の割り戻しを受けられるようにすればよい．このようなシステムでないと，植林はなかなか進まない.

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III. 持続可能な開発の事例研究
—サスティナブル・デベロップメント・グリーンフィールド—

新 田 義 孝*

III. A Possible Sustainable Development Greenfield

Yoshitaka NITTA*

1. 持続可能な開発とは

自然の恵みを最大限度利用して，豊かさを享受できるコミュニティーをつくること．そして，そのコミュニティーが，災害や戦争の無い限り，永遠に存続できる機能を持っていること．

2. 持続可能な開発が具備すべき条件

人々がある地域に定住するか，ある範囲内の地域を移動して生活を子々孫々まで維持していくのが難しくなってきた．その一つの要因は人口増加であり，もう一つは生活水準の向上を支えるのに不可欠なエネルギーの確保と，食糧生産の問題であり，最後の一つは環境破壊である．

1) 人口問題

ここでは，あるコミュニティーが鎖国状態でも自活していけることを想定する．したがって，そのコミュニティーが領土を開拓していかない限り，その地域に住める人口には限度がある．技術進歩は例えば1ヘクタール当たりの収穫量を増やすなど，人口の上限を拡大する作用があるから，既にその上限を超えた人口を擁する国やコミュニティーでは，技術導入や技術の開発・普及が必要になる．

2) 食糧問題

仮に一人一日あたり 2,600 kcal の食糧を必要とし，その四分の一を鶏肉から摂取すると考える．鶏の食べる穀物の三分の一が鶏肉になると想定し，穀物 100 g 当たり 250 kcal とみなす．2,600 kcal の四分の三が穀物からなので，直接食べる穀物は，

2,600 kcal×3/4×100/250＝780 g/日・人となる．

一方，鶏肉を介して食べる穀物は，

2,600 kcal×1/4×3×100/250＝780 g/日・人となる．

したがって，穀物に換算すると，人間一人一日当たり，1,560 g が必要になる．これに 365 を掛けると，一人一年間に必要とする食糧は，約 570 kg になる．

年 570 kg の穀物を生産するのに必要な耕作面積を推定すると，0.14 ha になる．

3) エネルギー問題

生活水準と人口増加の関係を，国民一人当たりのエネルギー消費量を生活水準の代表にとってプロットしてみると，一人一年間に石油換算 2.7 トンという値が人口増加をゼロにする必要条件のひとつと考えられることがわかる．

いま，世界人口 56 億人に，この値を掛けると 151 億トンになる．世界のエネルギー消費量は現在石油換算 80 億トン（88～90 億トンという数値もある）であるから，その約 2 倍にも相当することになる．したがって，従来通りのエテルギー消費形態で途上国の生活水準を向上させようとすると，人口が増えなくともエネルギーが不足する．

エネルギーは一人当たりの消費量が技術開発やライフスタイルなどに依存するところが大きい．一人当たり石油換算 2.7 トン/年という値は，それを化石燃料や電力に依存しなくとも，光合成を含めた太陽エネルギーや風力，水力あるいは，その他のエネルギーに求めてもよい．そうすることによってエネルギー不足をきたさないようにしようというのがここでのねらいの一つである．

4) 環境問題

一人当たり年間に石油換算 2.7 トンのエネルギー確保が来るべき 21 世紀の途上国における生活水準向上の目安になると推定したが，2.7 トン分の CO_2 が約 2 トン/年・人（炭素換算）で排出されると考えよう．2 トン/年

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の炭素を吸収固定するのに必要な熱帯林の面積は，0.2 ha 程度である．よって，一人当たりこの面積の森林を確保することが「持続可能性」の必要条件と考えよう．

5) 経済成長

人口増加が抑制され生活水準も一定以上に達すれば，物質的な満足は相当達成される．そして，マーズローが指摘するように，人間の欲求は物質的なものから精神的なものへと脱皮していくであろう．そうなると，エネルギー消費は頭打ちになるだろう．

そこまでに達するまでに，世界中が年率 3 乃至 5% の経済成長が必要であろう．

3. 究極の「持続可能な開発」のイメージ

昔は森林が茂り，生態系が生命を宿していた地域に，人間の生産活動が入り，生態系を破壊してしまった例が少なくない．そこにもう一度生態系を取り戻し，人間もその中に住んでコミュニティーを構築することを考える．

マングローブのある海域では漁獲資源が豊富であるから，すでに世界中で半分も破壊されたマングローブ林を復興することを考える．マングローブ林の背後にでんぷんを生産するためにサゴヤシを植える．その背後に，深層海水の冷熱を利用したグリーンハウス（温室ならぬ冷室）をつくる．そこで，温帯野菜などを栽培する．深層海水は栄養分に富んでいるので，養魚場にも併用可能である．

このコミュニティーの人口を 1,000 人と想定し，一家族平均 8 人とすれば 125 家族からなる集落である．先ずマングローブ林の植林であるが，10 年計画で 200 ha の森林を完成すれば，毎年 20 ha を伐採して植林しなおすことにより，200 トン以上の木材が生産できる．木材全てを燃やすわけではなく，パルプや建材などに用いて炭素として固定するなら温暖化の防止に一役買うことになる．かりに，燃料用にするとしても，もしそうしない場合と比べて，化石燃料を節約することになるので，やはり温暖化防止に寄与することになると考える．

200 ha のマングローブ林を植林するには，沿岸の幅 200 m，沿岸距離 10 km あるいは幅 500 m，沿岸距離 4 km の面積が対象になる．ここでは 500 m×4 km を想定する．

1,000 人分の食糧（穀物）を生産する耕地 140 ha を，幅 500 m のマングローブ林の背後に幅 350 m で確保する．栽培するのはサゴヤシ，水稲その他主食用穀物が中心である．深層海水の冷熱を利用して野菜栽培も行うが，無農薬栽培を行うために，害虫を餌として食べて育つホロホロ鳥などを飼育する．サゴヤシは樹幹に多量のデンプンを蓄積し，年一作の稲の 3〜4 倍，4 作の稲の 2 倍弱の生産が可能な樹木である．サゴヤシ林の背後にはサトウキビを栽培して砂糖の生産とその廃棄物を利用して，生分解性のプラスチックなどをつくる．

深層海水を利用して温帯野菜をつくるのだが，温度の低い深層海水をプラスチックチューブのなかを通して土壌の温度を下げ，同時に湿気から水分を凝縮させる．

一人当たり石油換算 2.7 トン/年のエネルギーを確保するには，4 ha 程度の太陽電池を屋根に配置する．深層海水の冷熱からえた冷房用のエネルギーもカウントするなどが考えられる．

バイオグループでは，以上のような想定を一例として，マングローブ林の植林をベースにした持続可能な開発を Sustainable Development Green Field と称して始めたところである．

Key Words: Sustainable development, Green field, Population, Food, Environment

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IV. 世界の沙漠化と日本の環境保護法の課題

井　口　　博*

IV. The Concept of the Environmental Protection Law and Prevention of Desertification

Hiroshi IGUCHI*

1. 世界の沙漠化と法的対応

1) 沙漠化の現状

沙漠化とは，「乾燥地域，半乾燥地域，乾燥半湿潤地域における気候上の変動や人間活動を含む様々な要素に起因する土地の劣化」をいう（UNCED・アジェンダ21）.

1991年のUNEP（国連環境計画）の報告書によると，世界で沙漠化の影響を受けている土地の面積は約36億ヘクタールで，これは地球上の全陸地の25%，世界の耕作可能な乾燥地の70% にあたるとされている．また沙漠化の影響を受けている地域の人口は世界人口の6分の1で，その影響としては (1) 灌漑農地の劣化（4,300万ヘクタール），(2) 降雨依存農地の土壌肥沃度と土壌構造の悪化（2億1,600万ヘクタール），(3) 牧草地の生産力の劣化（33億3,300万ヘクタール）がその主なものである．

しかし様々な国際的，国内的取り組みにもかかわらず，毎年の沙漠化のペースは6万平方キロ（四国と九州の広さ）といわれる．またこの沙漠化による経済的損失は年間約4兆円以上に上るとされ，沙漠化防止対策には，年間1兆円から2兆円もの費用がかかるとされている．この対策は遅れれば遅れるほどその費用が増大することもあって，沙漠化防止対策は世界の緊急課題である．

ところで今，地球環境問題として取り上げられているものは，沙漠化の問題の他に，(1) オゾン層破壊，(2) 地球温暖化，(3) 熱帯林の破壊，(4) 生物多様性の喪失，(5) 有害廃棄物の越境移動，(6) 海洋汚染などがある．沙漠化の問題を考える上でまず大切なことは，沙漠化の問題をこれらの地球環境問題とその背景にある貧困問題，人口問題などの中に正しく位置づけていくことであろう．

2) 法的取り組み

沙漠化防止についての本格的な国際的取り組みはごく最近になってはじめられた．その主なものは次のものである．

(1) 1977年・国連砂漠化防止会議 (UNCOD)

1968年から1973年ころにかけてのサヘル地域の干ばつを契機に国連総会で，沙漠化防止のための国際協力に関する決議が採択され，「砂漠化防止行動計画」(PACD) の採択，UNEP内に砂漠化防止部門を新設することが決められた．

(2) 1990年・UNEP主催「砂漠化の評価；現状と方法についての国際会議」(GLASOD)

(3) 1992年・「環境と開発に関する国連会議」（リオ・サミット）

「リオ宣言」・「アジェンダ21」において沙漠化防止対策の推進がもりこまれた．

(4) 1992年・第47回国連決議

1994年6月までの砂漠化防止条約制定をめざし，砂漠化防止条約政府間交渉委員会 (INCD) を設置し，5回の会合を行うことを内容とする決議を採択した．

3) 砂漠化防止条約（「深刻な干ばつ及び/又は砂漠化を経験している国々（特にアフリカの国）において砂漠化を防止するための国際連合条約」）

(1) これまでの経緯

1993年5月にINCDの第1回会合がナイロビで開かれて以来，第2回（1993年9月・ジュネーブ），第3回（1994年1月・ニューヨーク），第4回（1994年3月・ジュネーブ），第5回（1994年6月・パリ）の各会合が開かれて，1994年10月14, 15日にパリで100か国以上が出席して署名式典が行われた．わが国もこの条約に署名し，今後国会で批准手続がなされることになろう．条約の発効は，50か国が批准した後90日目からである．

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(2) 条約の内容

条約は前文と40か条からなる．その基本構造は，沙漠化の影響下にある開発途上国（影響締約国）に対して，沙漠化に関連する貧困問題，人口問題などを含んだ砂漠化防止行動計画を策定，実施することを義務づけ，他方，先進国（先進締約国）に対しては，この行動計画の実施にあたっての資金面，技術面での支援を義務づけるというものである．

(3) わが国との関連

条約では，先進国側に影響締約国への資金や技術面の支援（第6条）や資金供与（第20条）を義務付け，第1回締約国会議において資金源等についての組織を作る（第21条）こととしている．

(4) 条約の評価

約1年半という短期間に条約署名までなされたことに，沙漠化防止がいかに国際的な緊急課題であるかが示されている．また第5回INCD会合に120か国という多くの国が参加したということに，この沙漠化の問題が国際的拡がりを持っているかが現れている．

日本政府はこの条約の採択に積極的に寄与し評価を受けたが，今後はこの条約の中で資金，技術の面でどれだけの支援を実行できるかに大きな期待がかけられている．われわれは，これからの国際的貢献のあるべき方向としてその期待にこたえる必要があろう．

2. 日本の環境保護法

1) 国内的課題

わが国では1993年11月環境基本法が施行された．この環境基本法はまだなお課題を残しているが，新たな環境理念に基づいたものとして今後の環境政策の基本となるものである．

しかしその理念を実現するために，まだ個別の法律が追いついていない．例えば自然環境保全法はその目的，基本理念には格調高い立派な規定が置かれているが，実施規定は開発関連の法律に遠慮した非常に効力の弱いものである．また最近制定された「絶滅のおそれのある野生動植物の種の保存に関する法律」にしても，種の指定，生息地の指定による規制はごく限られたものでしかない．また廃棄物処理法などの環境保護のための規制もまだ実効性が弱い．他方，既存の法律，たとえば土地改良法とか公有水面埋立法，森林関連法などは未だ開発法としての仕組みを変えておらず，環境アセスメント法や環境関連の情報公開法も今後は必要であるが，いつできるかわからない状況にある．

また個々の事例を見ていっても，環境保護のために活動しようとするにはそのための情報へのアクセス，意見を表明する場，争うべき法的手段の確保が必要であるが，これらの点でも現状は余りにも不十分である．

2) 国際的課題

環境基本法にはその35条で，国の義務として，事業者の国外での事業活動に関し，「事業者がその事業活動が行われる地域に係る地球環境保全等について適正に配慮することができるようにするため，その事業者に対する情報の提供その他の必要な措置を講ずるよう努めるものとする．」としている．しかしこの条項は具体性がない努力規定であるから，その実効性を高めるためにはさらに一歩進めて経済的手段により環境配慮の方向に導くことが必要であろう．

この沙漠化防止においても国際的なNGOがINCDの会合に参加して，積極的な役割を果たしている．わが国ではカイロの人口会議で初めてNGOが政府代表に加わった．しかしまだわが国の環境NGOは資金面，会員数，さらに国際的なネットワークについて弱体である．政策提言や場合によっては政策の批判を通して行政に対するチェック機能を果たすのがNGOのあるべき姿であろう．

3. 結　び

わが国の環境保護法は，まだ立ち遅れが目立っている．個々の事例を見ても，まだ開発優先の考え方あるいはそのための仕組みが根強く残っている．しかし法律は急に変わるものではない．環境保護に対する個々の人々の努力あるいは企業の積極的取り組みが法や制度を変えていく原動力になる．

沙漠化防止に対するわれわれの努力も同じであろう．それに関わる者がこれらの変革の担い手であることを認識し，今後主体的に取り組んでいくことによって法や制度も変わっていくのではないだろうか．

Key words: Desertification, Environmental protection law, NGO

質疑応答

Q：大塚（清水建設）

世界の遺産になった白神山地に行ったことがある．遺産になったことで人が入る．人が入ると荒れてくる．遺産は5年毎の見直しと聞いているがこれではだめになる．法的に守る方法はないものか．

A：日本の場合，法でどこまで規制できるか難しい．日本の法は仕組みが緩やかで，開発はこの規制をうまく

よけながら施行している．そこでコア部しか残らなくなっている．自然遺産は何かとの兼ね合いを見つけるのは難しいが，対策として入場料をとるなど，これからは規制を掛ける必要がある．

Q：石川 (JTB)

自然保護のために，交通ガイドラインとして人数制限がある．ガイドラインにはチェック項目があり，上限を 20 人とするとある．自然保護の為にいろいろな制限があると思う．西表島に行って感じたことであるが，イリオモテヤマネコの保存と土地所有権と売買について問題になっている所がある．種の保存法に基づいてイリオモテヤマネコが出現する土地の売買について環境庁が規制できないのか．

A：何年か経てばできるであろう．生態系の保護のために保存すべきで，その動物が生息する区域は保護区にすべきであろう．環境庁が厳しい法を作り，損失補填すればできるであろう．環境庁は口を出せないのではなく，出さないのではないか．イリオモテヤマネコは現地の人からすれば神様とされているもので，かつては共存していた．しかし，時代と共に共存が難しくなってきている．何の補償もなしに生活を犯すような行政は地元に強制できないであろう．

Q：髙木（清水建設）

先生のお話の結びに「主体的に取り組んでいくことによって法や制度も変わっていくのではないだろうか」とあるが，我々も環境に対してまだやることが立ち後れているのではないか．

日本は開発を先行し環境保護が後回しにされており，一方，アメリカは環境を重視しているようであるが，歴史的に見て比較はどうか．

A：アメリカでもやはり開発優先であり，常に自然保護優先ではない．しかし，アメリカでは問題に対して論争ができる場が作られている．考え方の違いを公聴会，裁判所で論争できるような仕組みが日本では不十分である．

Q：遠藤（理化学研究所）

日本でも論争できるようにするためにどうしたらよいか．

A：まず，行政や企業から情報を提供させることが第一である．次に行政と地元の間で公聴会，公開討論会の制度を作ることである．

Q：遠藤

四国の水不足の例にあるが，農水，工水が余っていても，旧慣例法が優先で飲み水にできなかった．これは地域の中から法を作り，地方の法にすべきと思うがどうか．

A：その通りである．利水権は地域の人の声を反映する仕組みをつくることが必要である．

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V. 黄砂と日本海側山岳地帯の降雪

吉 川 友 章*

V. Yellow Sand and Snowfall in the Mountain Area of the Japanese Sea Side

Tomoaki YOSHIKAWA*

1. 日本海側の雪

冬の西高東低型の気圧配置に伴う日本海側の降雪は，山地はもとより海岸平野でも一夜に 1 m の新雪が積もることがあり，平野としては世界でも希な豪雪地帯である．その機構として，シベリヤからの寒気が日本海の最も幅の広い部分を渡り，下層大気が対馬暖流に暖められて日本海岸に近づいてから活発な積雲対流を起こすこと，暖流から蒸発，補給された多量の水蒸気が積雲内で一気に凝結することなどが指摘されている．また，上層と下層の気流の向きや熱的条件によって，本州内陸に背の低い高気圧ができ，日本海岸に局地前線が停滞する時に海岸平野に大雪（里雪）が降り，局地前線ができないときは山岳地のみに雪（山雪）が積もるという報告もある．さらに日本海側の雪は結晶形と雪質が独特で，氷粒のついた重たい樹枝状結晶やアラレ，ヒョウが多い．この雪質には日本海の波しぶきによる海塩粒子，都市交通・工業排煙からの大気汚染物質のほか，中国大陸からの黄砂が関係している．

2. 雪の結晶と雪質

中緯度から高緯度にかけては，真夏の低い雲からの雨を除き，図 5-1．のように，上空からの雪が成長しながら，そのまま着地する場合と，下層で融けて雨に変わる場合があるがいずれも降水に氷粒が関与する．対流圏中～上層ではおもに自然起源の微粒子（黄砂，宇宙塵など）を核とした氷晶ができており，下層から水蒸気が立ち昇ると気温と水蒸気量に応じてさまざまな形の雪片が成長する．低温で水蒸気量が少ない北海道などでは，針状，鼓状などが多いが，日本海上空などの－15 度以上の条件では樹枝状，扇状などが多い．さらに日本海上の下層では海塩粒や大気汚染粒子が微水滴をつくり，上空からの雪片に衝突して凍結する．氷粒つきの雪片は重くなって速く落下する．

降雪積雲は上空 850～700 hPa あたりの気流と沿海州，北朝鮮の山岳地形に関係して日本海上で列状に発生し，気流に送られて日本に達する．一方，日本海では対馬暖流が山陰北陸に沿って流れているため，積雪が沿岸に来てから急速に発達し，上陸の際の地形効果が加わって海岸平野に多くの雪を降らせる．海岸に局地前線があると，「里雪」が一層ひどくなり，雪雲が山地にさしかかると，地形上昇のために再び発達し，定常的に雪を降らせる．これらの現象は上層の偏西風波動に関係して，数日～1 週間続くことが多い．

3. 黄砂と大気汚染

実際に降った雪を分析してみると，疎水性の自然粒子が核になっていることが多く，過冷却水滴には塩粒や SO_4，NO_3 などの親水性の粒子が含まれている． 気象研究所では，雲物理チャンバー（気温，水蒸気量を精密に制御できる容器内に各種の微粒子を流入させ，凝結効果や氷晶効果を測定する装置）により，自然起源あるいは人工の粒子の水滴氷粒に係わる性質を測定している．これまでは機器の冷却能力の関係で，粒子の凝結効果のみ

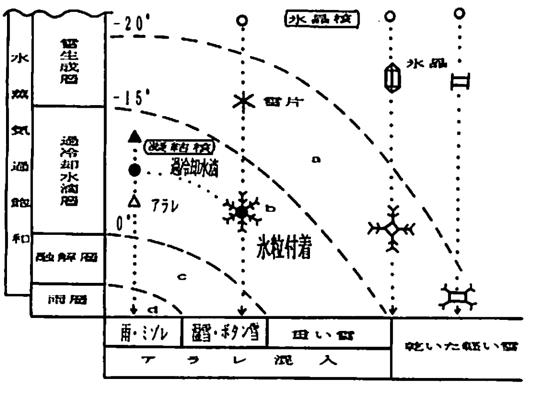

図 5-1． 低温域の水分挙動モデル．

* 気象庁気象研究所． 〒305 茨城県つくば市長峰 1-1 Tel. 0298-53-8625
* Institute of Meteorology. 1-1 Nagamine, Tsukuba-shi Ibaraki, 305 Japan.

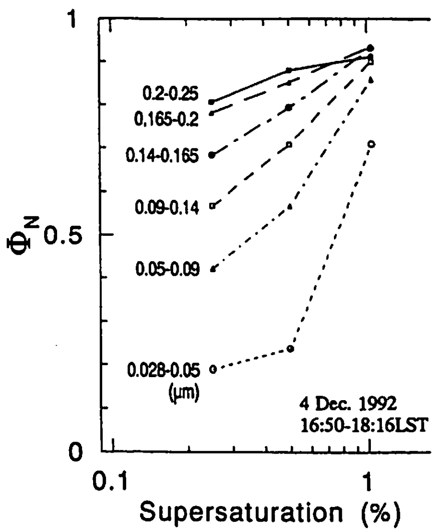

図5-2. 大気中エヤロゾルの雲粒移行率.
チャンバー実験による.

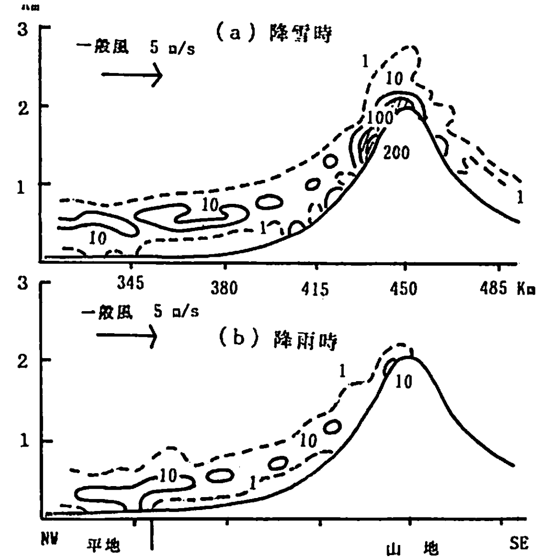

図5-3. 数値シミュレーション.
山脈に 5 m/s の一般風が吹きつけるとき, 同じ水蒸気量で雪と雨とした場合, 風上からの粒子の取り込み沈着量. 雪の場合は山稜に多く落ちるが, 雨だと風上山麓に達するまでにほとんど落ちる.

を測っていたが, 1993 年, 強力冷凍機を付加する改造が完成し, 氷晶効果も測り始めた.

図 5-2 に大気中に浮遊する微粒子のうち, 煤煙粒子の凝結効率を粒径別に測定した例を示す. これによると, 小粒子は過飽和度が小さいところではほとんど雲核とならないが, 粒径が大きくなると水滴をつくりやすいことが分かる. 各粒子を X 線分析した結果, 小粒子は炭素や疎水性の有機物であるのに対し, 雲核となった大粒子には水溶性物質が多く付着していた. 放出直後の煤煙粒子は凝結核として働きにくいが, 大気中に長く浮遊して, 大気汚染物質などの水溶性の粒子や溶液が付着すると, 水滴をつくることも確認された.

逆に, 疎水性の土壌や金属粒子は氷晶核として働く. 上空には粒子が細かく発生域が広い黄砂が浮遊していて, しばしば雪の核となっているのが検出される. ただし, 真冬は大陸が雪に覆われたり, 凍結しているために黄砂が上空に飛散しにくく, 大気中の粒子濃度が低い傾向がある. このため黄砂を積雲上空あるいは積雲内部の過冷却水滴ができやすい部分に人為的に補給すれば, 多くの水蒸気は水滴にならず, 雪片を生成するか, 上空からの雪片に蒸着して結晶を成長させることになる.

このほか, 黄砂の好ましい性質として, 化学的に弱アルカリ性で, 最近, 問題になっている酸性雨・雪を中和し, 山地の生態系を護る効果が期待される. 春先, 日本上空に黄砂が飛来したとき, 西日本の大気汚染測定局で SO_2 や NO_x が明瞭に低下したという報告がある. また, 中国の雨の ph が南部で酸性により, 北部で中性〜アルカリであることは雨の量や煙突高度のほかに黄砂が大きく効いているといわれている.

4. 降雪制御の可能性

日本海側の雪が親水性の粒子による過冷却微水滴のため, 上空からの雪片を重く湿った状態にして, 平野に早く落としていることから, 積雲中に人工的に疎水性の粒子を投入し雪の落下速度を落とすことで, 着地域を内陸や山地に移動させることが考えられる. 反対に積雪が多すぎるときは, 親水性粒子の逆効果により, 雪を海に早く落とすことも考えられる. 1991〜1993 年, 気象研, 土木研, 防災技研などの国立研究機関の協同プロジェクトとして, 日本海上と山形庄内平野で雪制御の可能性を探るために, 雪雲の構造探査と気象観測が行われた. 結果は雪雲中の特定域に多量の水滴ができ, 雪片の成長や落下速度を変えていることを明らかにした. このあと, 実際に雪雲に核を投入し, 効果を測定する第 2 期計画を立案している.

雨粒は粒径に応じて 5〜10 m/s で落ちるが, 雪片は普通 0.1〜0.3 m/s, 日本海岸の氷粒つき雪片は 1〜5 m/s で落ちる. そこで, 適切な時機と位置を選んで雪雲中に氷晶核を補給し, 微水滴の生成を抑制したり, 早期に凍結させれば雪片への付着を減らすことができる. いま, 雪片の平均落下速度 3 m/s を 0.3 m/s にした場合,

850 hPa の 20 m/s ほどの風で流される距離は数 km から 20 km に延び，着地点は海岸平野や都市を通り越して山地になる．降雪積雲は半径 3～5 km, 高度 3 km, 最盛期でも半径 10 km, 高度 5 km 程度で，風向に沿って次々に通るため，レーダ探査がやりやすく，スケールから考えても，数値シミュレーションをあわせて，各雲の適切な位置に粒子を投入することができる (図 5-3)．過冷却水滴の区域は 0.1～5 km で，微粒子を 10個/l ほど補給すればよい．サブミクロン粒子は 1l で 15 億個ほどあり，打ち上げ花火程度の爆発力と拡散範囲で目的が達成される．投入は海上の船，風上の島や半島からの打ち上び花火方式，高射砲あるいはミサイル方式，航空機による上空からの投下方式などが考えられる．

粒子として沃化銀が有効であることは知られているが，環境影響や経済効果を考えるとほとんど無尽蔵の中国の黄砂を微粒加工して使うのがよい．

5. 今後の課題

降雨，降雪制御のうち，予測の容易さ，雲の構造と大きさ，経済効果などから，日本海岸の雪の着地点を山地にずらせるのが最も現実的と思われる．今後，この計画を実行するにあたっては，次の事項を明らかにしておく必要がある．まず，粒子投入のタイミングと位置を雲中粒子映像ゾンデ，水滴・氷粒識別レーダなどで正確に探査し，最小限の粒子で最大の効果をあげる技術を開発しておくこと．同様な探査手法により，実験の効果を明瞭に判別する方法を確立すること．実験による被害も含めて，経済効果を算定する方法を用意すること．例えば，10 km 四方の市街地に 1 昼夜で 1 m の積雪があるのを半分にできたと仮定すると，区域の 10% を除雪するだけで 3～4 億円の経費が半分に節減される．実験に 2～3 億円かけても採算がとれるかもしれない．山地のダムより上流に増えた水資源がまた別にある．日本で唯一のクリーンな水資源を少なくとも平年並みに確保し，環境を保護し，交通の確保，除雪費の軽減等，メリットが多く，黄砂の加工，供給は沙漠産業のひとつにもなる．

Key Words: Yellow sand, Snowfall, Atmospheric pollution

SPECIAL ISSUE: DESERT TECHNOLOGY II, December 5–10, 1993, Kona, Hawaii

CONTENTS

Guest Editorial

Desert Technology II

Desertification (land degradation) is of worldwide concern. The process of desertification occurs on 70% of drylands, 3.6 billion hectares or a quarter of the total land surface of the world. The control and management of land degradation are being addressed by a wide range of disciplines. There is a critical need for cross-disciplinary communication and multidisciplinary efforts in seeking solutions to the complex issues and problems of desertification.

The first conference, Desert Technology I, was held August 4–8, 1991 in Santa Barbara, California. The main conference agenda was on collaborative research and development applications in the science and technology of arid lands. The co-chairs of this conference were Professor Kennith Foster, Director of the Office of Arid Lands, University of Arizona, USA, and Professor Isao Endo, RIKEN, Saitama, Japan. Fifteen conference papers were edited and published by the University of Arizona. The cosponsors of Desert Technology I were the Engineering Foundation, USA, the Engineering Academy of Japan, and the US Department of Agriculture.

The second conference, Desert Technology II, was held December 5–10, 1993 in Kona, Hawaii. The objectives of this conference were to address scientific and technical issues on desert technology and identify interdisciplinary issues, problems and management options on desertification. The co-chairs of this conference were Professor Isao Endo, RIKEN, Saitama, Japan, Professor Kenneth Tanji, University of California, Davis, USA, and Professor Alan Bull, University of Kent, UK. They were ably assisted by Professor Toshinori Kojima, Seikei University, Tokyo, Japan. The cosponsors of Desert Technology II were the Engineering Foundation, USA, Bioprocess Engineering Research Group in Japan, the Desert Technology Working Group of the Japanese Association of Arid Land Studies, and the Division of Agriculture and Natural Resources, the University of California.

The proceedings of Desert Technology II is being published by the Journal of Arid Land Studies. The proceedings consist of Principle Science and Technology Issues and Problems in Desertification identified by the participants , and 12 contributed papers on Environmental and Energy Resources, Biological Diversity, and Water Resources and Their Effective Utilization.

Desert Technology I and II will be followed by Desert Technology III to be held October 15–20, 1995 at Lake Motosu, near Mount Fuji, Japan. Desert Technology III will take a broad-interest in the engineering and scientific aspects of protection against desertification and land degradation, and the effective development of deserts.

Professor Kenneth Tanji
University of California, Davis
Professor Isao Endo
RIKEN
Professor Toshinori Kojima
Seikei University

Desert Technology II
An Engineering Foundation Conference

5-10 December, 1993

Keauhou Hotel, Kona, Hawaii

Program

5 Dec. (Sun.)

14 : 00– Registration & Paper Submission

19 : 30–21 : 00 Opening Reception

6 Dec. (Mon.)

09 : 00–09 : 20 Opening Remarks, I. Endo

09 : 20–10 : 30 Plenary Lecture

- Kenneth K. Tanji: Principle Science and Technology Issues and Problems in Desertification—I*

10 : 45–12 : 45 Environmental and Energy Resources—I: Presiding, S. Link

- Toshinori Kojima, Yoshitaka Kakubari, Satoshi Matsuda and Hiroshi Komiyama: Afforestation of Arid Land for Carbon Fixation
- James A. Young, Robert R. Blank and William S. Longland: Reclamation of Open Pit Mining Spoils in Temperate Desert Environments

19 : 30–21 : 00 Environmental and Energy Resources—II: Presiding, J. Young

- Dayin Li and Isao Endo: Design of the Integrated Renewable Energy System for Oasis

7 Dec. (Tue.)

09 : 30–12 : 45 Biological Diversity—I: Presiding, J. Young

- Shigeru Kato, Fumito Takagi and Yoshitaka Nitta: Challenge for Desert Rehabilitation through Sustained Mangrove Management***
- André Läuichli: Engineering Plants for Saline Desert Environments—Is it feasible ?**
- Anson E. Thompson: Opportunities and Constraints for Developing New Industrial Crops Adapted to Arid Lands

19 : 30–20 : 30 Biological Diversity—II: Presiding, A. Thompson

- James A. Young, Robert R. Blank, Debra E. Palmquist and James T. Trent: Allenrolfea Deserts in Western North America

20 : 30–21 : 00 Discussion

- Principle Science and Technology Issues and Problems in Desertification—II*: Moderator, K. Tanji

8 Dec. (Wed.)

09 : 00–12 : 30 Water Resources and Their Effective Utilization—I: Presiding, K. Tanji

- Kunio Horiuchi, Masayuki Inoue, Kiyotaka Tahara, Tadayasu Mori and Toshinori Kojima: Effect of Super Absorbent Polymer on Water Movement in Soil
- Steven O. Link, Norman R. Wing and Glendon W. Gee: The Development of Permanent Isolation Barriers for Buried Wastes in Cool Deserts: Hanford, Washington
- Hiroyuki Ii: Effective Porosity, Longitudinal Dispersivity and Hydraulic Conductivity of a Sedimentary Formation by Laboratory Tracer Tests and Field Tracer Tests

19:30–21:00 Water Resources and Their Effective Utilization—II: Presiding, I. ENDO
Yuichi ISHIKAWA, Sadao MIZUNO, Minoru ISHIBASHI, Hirofumi INADA, Noriyoshi KANEKO, Motoya TAKAGI and Satoshi MATSUMOTO: A non-irrigation System Using the Dew Condensation Caused by Diurnal Range of Air Temperature in Arid Sand Dune Area
Kenneth K. TANJI: Saline Drain Water Reuse in Agroforestry Systems

9 Dec. (Thu.)
09:00–10:00 Water Resources and Their Effective Utilization—III: Presiding, T. KOJIMA
Hiroshi KOKUBU: Water Resources from Iceberg of Antarctica and Undersea Reservoir
10:30–12:30 Discussion
Plans for Publication of Conference Papers: Moderator, I. ENDO
Principle Science and Technology Issues and Problems in Desertification—III*: Moderator, K. TANJI
19:30–22:30 Hawaiian Luau at the King Kamehameha Kona Beach Hotel

10 Dec. (Fri.)
09:30–10:30 Discussion
Proposal for Desert Technology III: Moderator, I. ENDO
Anticipated Products of Desert Technology II: Moderator, K. TANJI
11:00–11:30 Closing Remarks, I. ENDO and K. TANJI

Notes: All contributed papers were reviewed by referees, and corrected based on their critical comments. *The discussion results are summarized as a report entitled "Principle Science and Technology Issues and Problems in Desertification". **Withdrawn for publication. ***Presented by H. II.

沙漠研究 4, 147-151 (1995)
Journal of Arid Land Studies

Principle Science and Technology Issues and Problems in Desertification

A contribution by conference participants*

In his plenary lecture Professor Tanji initiated discussions on scientific and technical issues in desert environments. And the participants, throughout the duration of the conference, identified and compiled a broad listing of issues and problems. This paper summarizes them into Energy Resources, Water Resources, Biological Diversity, Food Resources, Urban Dynamics of Oasis, Transportation Systems, New Materials and Cross-Cutting Technologies, Protection Against Desertification, and Monitoring and Environmental Assessment.

I: ENERGY RESOURCES

- Afforestation in arid lands has potential.
- Overutilization of biomass leads to land denudation and subsequent erosion and sediment production.
- Shortages in energy sources may lead to using biomass for cooking fuel and animal feed.
- A potential exists for solar cooking instead of using biomass and fossil fuels.
- Increased CO_2 may increase water use efficiency by plants.
- Development of solar cells and windmills to harness wind energy have substantial potentials.
- Impacts from high winds and sand will damage solar cells and windmills. Damages to solar cells may be reduced with wind breaks such as plants and fences.
- Improvements in batteries are needed to store energy, especially for domestic uses.

II: WATER RESOURCES

- A dependable water supply is crucial to sustained development in the desert.
- Marginal quality waters should be used until no longer usable.
- Water harvesting of meager rainfall for agriculture should be further explored.
- Remote sensing may help locate fossil waters.
- Problems exist on overdrafting ground water basins because of inadequate rates of recharge of ground water bodies.
- Competition for water exists and reallocation of water from agricultural uses to other uses may be necessary.
- Presence of excess trace elements of concern as well as deficiency in soils, food and forage should be recognized.
- Economics of desalination depend on fresh water needs.
- Desalination process produces residuals such as brine which needs to be managed such as disposal or salt harvesting.
- Biotechnology is challenged to improve salt tolerance and drought tolerance of plants.
- Remediation or cleanup may be needed to improve quality of surface and ground waters.
- Source control of nitrates and pesticides are needed to protect water resources.
- Improving irrigation water management and practices will increase water use efficiency.
- Deserts used for storage of toxic and hazardous materials will require adequate protection.

III: BIOLOGICAL DIVERSITY

- Importance of soil micro-organisms should not be overlooked, in addition to higher plants and animals.
- Changes in biologic diversity may be site

* Isao Endo, RIKEN; Kunino Horiuchi, Seikei University; Hiroyuki Ii, Shimizu Corporation; Yuichi Ishikawa, University of Tokyo; Toshinori Kojima, Seikei University; Hiroshi Kokubu, Kajitani Engineering Company; André Läuchli, University of California, Davis; Steven Link, Pacific Northwest Laboratory; Kenneth Tanji, Univeristy of California, Davis; Anson Thompson, USDA Agricultural Research Service; and James Young, USDA Agricultural Research Service.

specific and very complex to evaluate.

- Loss of germplasm is of concern.
- Natural historical diversity vs changes brought about by human habitation need to be evaluated.
- Importance of N fixation by blue green algae and others are important in desert ecosystems.
- Cryptogamic crusts-microbes, lichens, moss, and non-vascular plants-affects water infiltration, plant cover, erosion, etc.
- Fire and off-road vehicles may cause adverse impacts to desert ecosystems.
- Effects of increasing soil salinity will decrease the number of plant species.
- New industrial crops, *e.g.* oil seed crops, need to be explored.
- Agroforestry systems can provide trees and shrubs for fuel, animal feed, and construction materials.
- Sustainable agriculture require control on grazing animal units and land degradation.

IV: FOOD SOURCES

- Water is the most limiting resource for food production.
- Integration of nomadic vs settled farmers require attention.
- Adequacy of nutrition is of concern in arid zones.
- Storage of perishable goods and food preservation, including drying and salting, are of paramount importance.
- There is heavy reliance on animals for food, clothing and shelter; and for monetary or bartering purposes.
- Is there a catalog of nomadic food production systems?
- Seasonality in the availability of foods must be recognized.
- Transportation of food stuffs is a frequent problem.
- Finding new sources of food not presently used or used in the distant past should be pursued.
- Polymers and ground cover may be used to prevent soil erosion and improve water infiltration rates, and hence increase food production.

V: URBAN DYNAMICS OF OASIS

- There is a need to consider energy, water, food, and wastes in designing oasis.
- Wind, solar and biomass sources should be considered as energy sources.
- Marginal quality waters should not be overlooked as potential usable water resources.
- Enhanced food production may be achieved through glass and plastic houses.
- Merchandising (industrial) should be considered as an important economic unit.
- Health care and hospitals and other medical facilities need to be provided.
- Migration of population in and out of oases is a problem.
- Transportation network within and outside of oases require attention.
- The quality of life may be enhanced by proper land use planning, political management, and architectural design.

VI: TRANSPORTATION SYSTEMS

- Adequate planning and design for streets, roadways, and footpaths are essential.
- Effects of winds, especially moving sand dunes, need to be managed.
- Vegetation, wind breaks, polymers, etc., may be used to protect from shifting sand dunes.
- There is a ususal need for large areas for grazing animals.
- Adequate transportation between centers of population are required.
- In addition to water and transportation systems, electricity and communication systems need to be developed.
- Is nomadic society better in the deserts?

VII: NEW MATERIALS AND TECHNOLOGIES

- The potential for non-food, non-feed industrial and pharmaceutical plants and other biologically active plants should be considered in deserts.
- Cacti fruits are nutritious for human consumption and cacti pads for animal feed, and agave for alcoholic drinks.
- Greater use of fiber crops require cross over technologies.

- o New materials to capture solar energy and water resources should be explored.
- o Impermeable polymers may be used for storage and transportation containers for liquids.
- o Absorbent biodegradable polymers have multiple uses.
- o Enhancement of native plants, *e.g.*, hardwood ecosystem, endangered plants, xeriscape, should be considered.
- o Appropriate technologies should be promoted in underdeveloped sites.

VIII: PROTECTION AGAINST DESERTIFICATION

- o Key issues in the deserts include water, soil, food, animals, and energy resources.
- o Water

—New water supplies should be sought: mining ground waters, desalting brackish waters, reusing wastewaters, importing water.

—Water harvesting have some potentials: techniques to collect runoffs, soil surface sealents (polymers, sodium) to increase runoffs; capture fog and dew water; seed rain clouds; and water vapor harvesting in agriculture.

—Water conservation measures include rationing water consumption; use of native vegetation-xeriscape; improve water application efficiency-increase distribution uniformity, microirrigation/trickle irrigation, real-time irrigation scheduling.

—Drought and salt tolerant plants require further research.

- o Soil

—Protection from erosion is achieved by maintaining vegetative (biological) cover; stabilizing soil aggregates and sand dunes with vegetation and polymers; construction of wind breaks-shrub and trees, fences.

—Establish desert cover and pavement (gravel).

—Protection and management of soil salination; provide adequate drainage-surface and subsurface; adequate leaching to maintain salt balance in crop root zone; pump and use shallow ground waters; plant salt tolerant species.

—Off-road vehicle usage should be controlled.

—Vesicular crusts protect surfaces of playas and other depressions.

- o Food and Crops-Cropping patterns

—Change food sources and diet, *e.g.*, by substituting nuts, beans and cereals for proteins instead of meat.

—Use drought tolerant plants for landscape, food and fiber crops; they have smaller water requirements.

—Practice dryland farming-fallow/planting cycles to conserve soil moisture.

—Practice appropriate grazing practices.

—Integrate livestock and cropping.

—Timing of planting date is important for food production in deserts.

—Inappropriate balance in land use between cropping and grazing should be avoided.

—Water transfer from agricultural to urban uses may occur during water shortfalls.

—In some instances land must be abandoned due to degradation and when resources become available degrade land should be restored.

—Invasive plansts may affect grazing lands, *e.g.*, yellow star thistle and change ecology of desert and may pose a fire hazard.

- o Energy Sources

—Requires more energy to mitigate desertification.

—Maximize the use of various energy sources with wind mills, geothermal sources, biomass cogeneration, fossil fuel, solar panels and ponds, and glasshouse culture of food crops.

—Geothermal energy sources in deserts should be fully exploited.

—Solar gradient ponds offer a source of generating electricity.

IX: MONITORING AND ENVIRONMENTAL ASSESSMENT

- o Key issues are what to measure and how?, short vs. long term monitoring, and use of simulation modeling and risk assessment.
- o Agroclimate weather station is essential for measuring precipitation, wind speed and direction, relative humidity, air and

soil temperatures, and solar radiation.

- Remote sensing, *e.g.* satellite and airplanes; provide GIS databases.
- Reference ecology and trends ought to be monitored.
- Monitoring Water Quality

—Drinking water-potability; public health standards: fecal coliform, nitrates, trace organics, pesticides and solvents, metals and other toxic trace elements.

—Irrigation water-salinity, sodicity and specific toxic ions.

—Industrial waters-suspended solids, hardness, pH, and alkalinity.

- Monitoring Water Quantity

—Inventory of fresh water, brackish waters, and waters of marginal quality.

—Reuse (recycle) waters until no longer usable.

—Cleanup and treatment of marginal quality waters.

—Use of tracers and stable isotopes for ground water; "water witching" or water dousing.

—Remote sensing-evapotranspiration; underground water basins (fossil water under dry stream beds).

- Monitoring Soil Quality

—Soil quality: fertility status-nutrients, soil organic matter; salinity and sodicity.

—Soil quality: physical status- bulk density, compaction, permeability, profile depth.

—Below ground ecosystem: soil microbes and animals.

—Alleopathy-production of secondary compounds and interplant competition.

- Monitoring Air Quality

—Particulates-agricultural wind erosion, PM 10, salt dust storms.

—Gases and aerosols-ozone, oxides of nitrogen and sulfur, carbon monoxide.

—Biogenic trace gases-methane, hydrogen sulfide, carbon dioxide, and animal waste gases.

—Smokestack emissions-mining, coal-firing plants.

—Paleoclimate and ecosystem-changes, time dimension.

- Monitoring Food Quality and Quantity

—Quality: nutritional value, palatability.

—Inspection for contaminants: microbes, heavy metals, pesticides.

—Quantity: caloric requirements, vitamins.

—Diversity in food diet.

- Monitoring Biological Diversity

—Innovative measures: monitoring insects reflecting trophic levels-marker species.

—Marker environmental characteristics, *e.g.* water quality, quality and quantity of food supply and habitat.

—Increase in invasive species.

—Evaluate ecosystem status from functional perspective-landscape ecologic principles and structure.

—Genetic diversity-community diversity-ecosystem diversity.

—Issues of scale from areal remote sensing to point measurements.

- Simulation Modeling

—Systems, subsystems, process levels.

—Conceptual models-simplified, compartmental, pools and fluxes, management oriented.

—Dynamic models-complex, process level, small time and space increments, data intensive, research-oriented.

—Optimization models-linear programming, cost/benefit analyses, operational research, transportation, energy models.

—Risk assessment models-coupling physical/biological base models for impact assessment, *e.g.*, Hanford site; include economics.

—Stochastic models (nondeterministic).

—Changes in environmental values and costs need to be assessed.

—Cost of not doing anything; additive costs due, *e.g.*, to global climate change.

- Examples of Modeling
- Hydrologic (water) Models

—Soil-plant-atmosphere continuum.

—Water harvesting potentials, watershed modeling.

—Vadose zone/ground water modeling: specific yeield, ground water overdraft, solute and contaminant transport.

—Application of numerical methods, *e.g.*, finite element modeling.

—Global climate change modeling.

—Ecosystem modeling: ncorporation of bio-

logical processes.
—Use of tracers and stable isotopes.
—Strategies for remediation of contaminants.
- Food and Forage Production Models
—Energy flow models.
—Carrying capacity-animals.
—Soil fertility, water and salinity stresses.
—Crop production function modeling.
—Transformations and transport of solutes, *e.g.*, nitrogen.
—Soil-plant-atmosphere continuum models.
- Wind and Water Erosion Models.
- Long distance transport of atmospheric pollutants and deposition.
- Precipitation-runoff: watershed, croplands.
- Stream flow, ground water recharge, erosion, sediment production and transport.
- Wastewater treatment and recycling: treatment processes, desalting technologies.
- Urban dynamics and design of oases: water resources, energy sources, food production, transportation.

Summary

In summary, a long list of issues and problems in respect to desert technology and desertification has been compiled. This listing is incomplete and reflects the knowledge base and biases of the conference participants. There is a need to prioritize these issues and problems. Many of them are cross-cutting and require multidisplinary approaches in seeking solutions and management alternatives. Only a small portion of the stated issues and problems are addressed in the 12 conference papers that follows.

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Afforestation of Arid Land for Carbon Fixation

Toshinori KOJIMA*, Yoshitaka KAKUBARI**, Satoshi MATSUDA***
and Hiroshi KOMIYAMA****

1. Introduction

The main cause of global warming issue, *i.e.*, the primary source of carbon dioxide emission is fossil fuel burning. Therefore, the development of alternative energy sources and the reduction of energy consumption are the most essential measures. The realization of such measures, however, is not easy and limitations exist. Various measures of recovery and disposal of CO_2 have been proposed. In these measures of CO_2 fixation, only the ocean, underground and surface plants (ecosystem) are thought to be the feasible final sinks from the view points of total energy balance. Furthermore, CO_2 recovery from dispersed sources, *e.g.*, those from homes and vehicles, is impossible. Greening of arid and semiarid lands may be one of the feasible measures of CO_2 fixation, because the surface biosphere has a large potential to fix carbon and the change in land management is expected to be acceptable locally and globally. Furthermore, the biosphere converts carbon dioxide into carbon only using solar energy which is difficult for us to use effectively and economically.

There exist, technological problems such as the supply of energy to make and/or transport water to the wide area of deserts, decision of the most appropriate greening strategy, and so on. Technology assessment and optimization of the agronomic aspect of the greening project are essential for the fruitful result against the greatly increased CO_2 fixation.

First, in the present study the important role of greening of arid and semiarid lands in the carbon dioxide problem is demonstrated by showing the data on carbon cycle and stock in this planet. For more than one year a project to assess the such possibilities has been conducted under the sponsorship of RITE, Research Institute of Innovative Technology for the Earth, and The Japan Gas Association. Second, the activity of the project is explained. Lastly, the methodology of the evaluation of the effects of the greening on the problem is explained and the future scopes are proposed.

2. Global Carbon Cycle and Stock

1) Carbon cycle

The carbon balance in its cycle is summarized in Fig. 1. The amount of carbon dioxide from fossil fuel utilization is estimated from the energy data. The amount of carbon dioxide accumulated in the atmosphere is also calculated from its concentration change. The amount of carbon dioxide released by the destruction of forest is estimated from the deforestation rate, more than 10 Mha/y, and carbon stock shown in the following section. The accuracy of their estimations is low. The last part of the earth is the ocean. The amount of carbon moving between the atmosphere and the ocean has been estimated using models while the value may not be valid. From the mass balance, more than one to two Gt carbon is found to be missing. The candidates for the missing sink are shown in Fig. 1.

2) Carbon stock

The amounts of carbon stock in various ecological systems are shown in Table 1.[1,2,3] The difference between the carbon in living plant in tropical forest and that in grass land is given as 170 t/ha by WOODWELL.[1] The amount of carbon released from destruction of forest is expected to be 1.7 Gt/y. Taking the inaccuracy into account, the value of 1.5 to 2 Gt/y are

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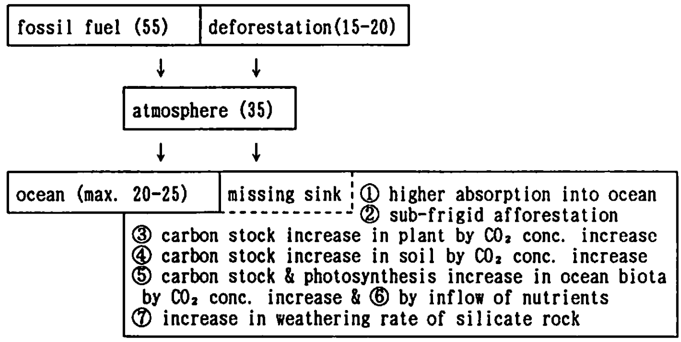

Fig. 1. Global carbon balance (unit: 10^8 t–C/y).

Table 1. Carbon amount, primary net production and time constant of ecosystem.

Type of ecosystem	Area	Organic	Concentration	Net	Production	Time const.
		alive, dead	alive, dead (total)	amount	conc.	alive (total)
unit	10^8 ha	10^8 tC	tC/ha	10^8 tC/y	t/ha/y	y
tropical	18	2700, 1260	150, 70 (220)	136	7.5	20 (29)
forest	[24.5	4610, 1470	188, 60 (248)	222	9.1	21 (27)]
temperate	12	1300, 1530	110, 130 (240)	71	5.9	19 (40)
forest	[12.0	1740, 1080	145, 90 (235)	67	5.6	26 (42)]
sub-frigid	13	1100, 2250	85, 175 (260)	43	3.3	26 (79)
forest	[12.0	1080, 1560	90, 130 (220)	43	3.6	25 (61)]
bush	8 [8.5]	400 [220], 800	50 [26], 100 (150)	24 [27]	3.0 [3.2]	17 [8] (50)
marsh	4 [4]	40 [135], 800	10 [34], 200 (210)	12.5 [31]	3.1 [7.8]	3.2 [4] (67)
trop. grass	13 [15]	70 [270], 1040	5 [18], 80 (85)	19.5 [61]	1.5 [4.1]	3.6 [4] (57)
temp. grass	9 [9]	90 [63], 1350	10 [7], 150 (160)	22.5 [24]	2.5 [2.7]	4.0 [3] (64)
farm land	14 [14]	140 [63], 840	10 [4.5], 60 (70)	42 [41]	3.0 [2.9]	3.3 [2] (23)
tundra	8 [8]	40 [23], 1600	5 [2.9], 200 (205)	4.0 [5]	0.5 [0.6]	10 [5] (410)
(semi)desert	45 [42]	50 [61], 260	1 [1.5], 6 (7)	9.0 [7]	0.2 [0.2]	5.5 [9] (35)
abandoned	5 [—]	150 [—], 400	30 [—], 80 (110)	12.5 [—]	2.5 [—]	12 [—] (44)
Land	149	6080, 12130	41, 81 (122)	396	2.7	15.4 (45)
(subtotal)	[149	8265,	55.5, ( )	528	3.54	15.7 ( )]
river mouth	1.4	6.3	4.5	10	7.1	0.63
coastal	2	5.4	2.7	7	3.5	0.77
upwelling zone	0.4	0.04	0.1	1	2.5	0.04
continl. shelf	27	1.2	0.045	43	1.6	0.03
other ocean	332	4.5	0.014	187	0.56	0.02
Sea (subtotal)	361	17.4, 9000	0.048, 25 (25)	248	0.69	0.07 (36)
Global	510	6100, 21000	12, 41 (53)	644	1.26	9.5 (42)
(total)	[510	8280,	16, ( )	776	1.52	10.7 ( )]

literature[1,2,3] note: [ ] is the data from different source.

presented in Fig. 1.

The necessity, superiority, and advantage of the present measures of afforestation of desert for carbon fixation derived from Fig. 1, Table 1, and other published data are summarized as follows: First, the surface biosphere has played an important roll of source of CO_2 since the appearance of man. Presently, 1.5–2 Gt–C/y is emitted by destruction of the tropical rain forest. The cumulative contribution of surface biosphere is almost double that from fossil fuel. This indicates that the plant has been impor-

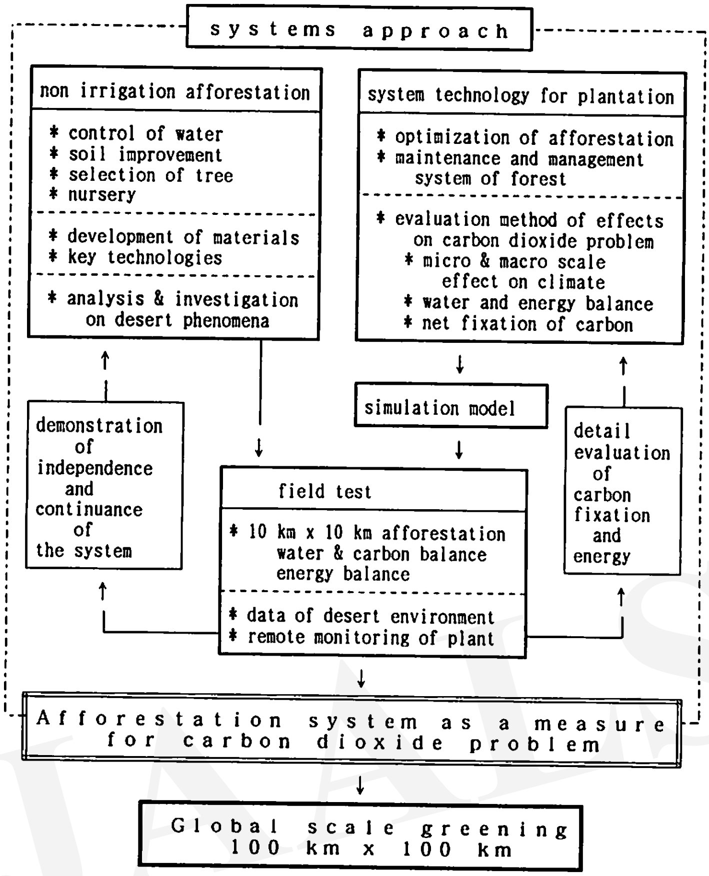

Fig. 2. Scope of the present project.

tant in change in the carbon cycle. Second, accumulation of CO_2 in the atmosphere is around 3.5 Gt–C/y. If we could stop the destruction of the tropical rain forest (around 10 million ha/y now), and afforestation progressed at the same rate as above, the accumulation would be stopped. The present evaluation is on the basis of the assumption that the missing sink is forever. To know what the missing sink really is, is also essential. Third, the global arid land area including desert, grass semiarid land, salt affected land, and unused land is more than 6 billion ha, which is equivalent to six hundred years' measures based on the above area of desired afforestation per year. This term is almost equivalent to the ratio of ultimate amount to the production rate of fossil fuel resources. Fourth, the reduction of carbon dioxide to carbon need equivalent amount of energy to that produced by fossil fuel combustion. Afforestation enables it by using solar energy which has not been used artificially. What is more important is that the produced carbon is naturally stocked in it. This means that this measure essentially needs no energy, man power nor cost.

3. Actions for Afforestation of Arid Land for Carbon Fixation

For more than one year, a project to assess the above possibilities has been conducted under the sponsorship of RITE, Research Institute of Innovative Technology for the Earth, and The Japan Gas Association. The chair of this project is Prof. Kaya, The University of Tokyo. In the present paper, the activities of the project is summarized. As to the detail, please refer to the interim report of the projects.[4)]

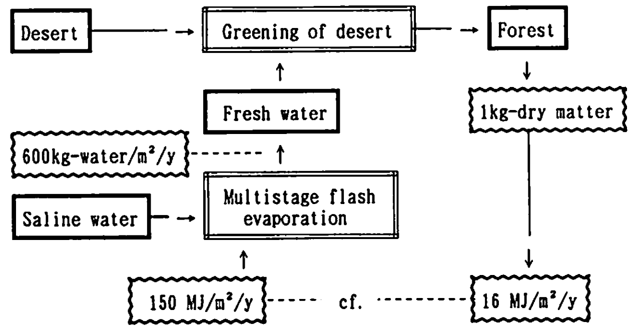

Fig. 3. Energy balance in greening of desert: flash evaporation.

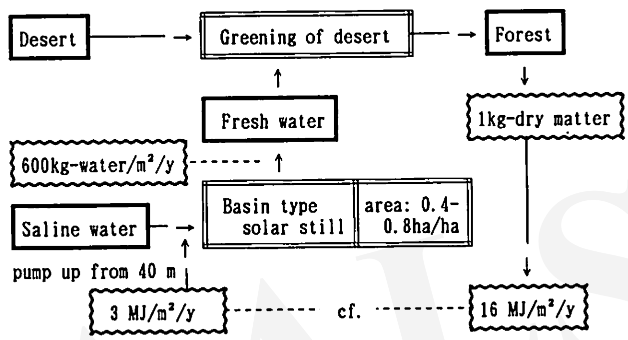

Fig. 4. Energy balance in greening of desert: solar still.

1) Outline of the project

The outline of our project are schematically shown in Fig. 2. Our final goal is the plantation of a area of 100 km×100 km, *i.e.*, 1 Mha. This area is equivalent to 0.15–0.2 Gt-C and around 10% of the carbon dioxide emission by the deforestation. This means that almost ten places with 100 km×100 km area should be greened per year to prevent the carbon dioxide problem.

The area of 1 Mha is large. We can expect additional scale merits. First is the expectation of the change in the meteorology of desert, second is the systematic utilization of water, and third is the construction of the social and ecosystem.

Features of the present study are as follows: (1) the systematic approach. The single and multiple effects are investigated. No target area is focused, (2) the macro balance, especially macro balance of water and carbon in the system, (3) the combination of the ecotechnology, *e.g.*, micro catchment and sand fixation by grass, and hightechnology, *e.g.*, biotechnology and functional materials, from engineering and technology view points.

2) Technological problems in water supply and utilization

While the importance of the greening of the arid and semiarid land was stressed, the supply of water is essential. In addition, the critical evaluations of effects and necessary man power are required. Furthermore, after stopping of growth of wood, no net accumulation is expected.

In the present section, the problems in water supply and utilization are mentioned. In some countries, water is manufactured using oil. The energy balances of the systems for water management were calculated.[5] Typical result is shown in Fig. 3 in which water is produced from multieffects flash vaporization. In this case, total energy balance was found to be negative; more energy input than the energy production from the constructed forest necessary for the afforestation of the arid land. The results in Fig. 4 shows fresh water produced from saline sea water with a solar basin still, most of the energy supplied from solar. The energy balance was positive, however, the area for setting basins was at least half of the afforestation area. Such evaluation as above was on the assumption that no natural water is available. It should be stressed that the natural precipitation should be effectively utilized.

The description of the water and salt movement in soil and the effective use of various kind of materials to save the water supply are also essential, in addition to the development of effective production of the water from saline water.

An important feature of the project is the macroscopic improvement of water supply and utilization. If the water is recycled, the amount of available water, b, is given as follows, where a is natural water supply and x is fraction of water recycled. Here, the water used to make forest was assumed to transpire, though the fraction of evaporation should also be taken into account for the strict discussion.

$$a+bx=b \quad \text{or} \quad b=a/(1-x)$$

The present expression indicates that the available amount of water is increased by both the increase in precipitation and the fraction of the recycle. The former is realized by the increase in steam content in air, *i.e.*, acceleration of the evaporation from the sea in the vicinity of the desert or saline water, and by the increase of the possibility of the rainfall, *e.g.*, formation of the upward air current and artificial trap of the night dew. For the increment of the recycled fraction, first the technique of irrigation is essential and second, the reservation of water to prevent the run-off, *e.g.*, underground dam. The selection of the afforestation site is also important because the transpired steam can be recycled if the afforestation was conducted at the area of upward air current. The macro positive feedback effects are also expected.

3) Technological problems in greening and soil management

The excellent technologies in desert region were long accepted traditionally by native people, corresponding to desert environment. The technology without supporting by desert environment is not accepted in such an environment.

What is the basic principle under these technologies? The principle is shown as follows; to get good water, stability and to use water under complete management such as Ganat (Karez) in middle east and China.

The availability of water controls the scale of village, cultivated area and amount of cattle. In developing irrigation system under the limitation of water use in desert area, annual agricultural products increase rapidly. We must point out the environmental problem like the case of Aralu-sea caused by great quantities of water use.

In developing the desert area by greening we must calculate the balance of minerals to escape the environment catastrophe. For the greening of arid land we need information about eco-physiological characteristics of plants. It is important to investigate the field condition of soil and climate. *Acasia albida, A. nilotica, A. senegal, Eucalyptus species* and *Prosopis spicigera* are recommended for planting on the semiarid region.

In developing the cultivation technology of arid land agriculture it is important to consider the water- and salt-balance on the soil, nursery, irrigated area and level of water characteristics. The combinations of traditional cultivation methods and modern agricultural methods are pointed out to develop the productive efficiency on these area. The combination methods of agriculture, forestry and rotation of crops are introduced recently in this area. The traditional agricultural system is steady from environmental condtion, however, it is very low in crop production.

The management of cultivation is influenced with natural- and social-, economical conditions, in addition to the life style and culture. Cultivation technology and system shall be designed in connection with a level of environmental equipments from the view point of developing agriculture. We point out the problem as follows; (1) the project for the establishment of infrastructure shall be taken the right to receive payment in preference to others, arrangement of land-ownership, traffic and transportation system, education system, domiciliation of a nomadic people, social-economical equipment to farmer, developing water resources and distribution to individual farmer, (2) management of cultivation, irrigation system and planting designed as a total system.

For sustainable agricultural management, we introduce suitable agriculture systems as follows; conservation of fertility, soil conservation, management of rain water, decreasing of run-off water and planting for a conservation of soil surface. It's natural to select high-tolerant crop, against salinity and drought. The next important point is developing plants with high fixing capacity for carbon dioxide. The following informations are essential; characteristics of plant in CO_2 fixation capacity, carbon-cycling in the forest ecology, description of carbon sink/sources and also recent researches on analyzer about CO_2 fixation of forest. Algorithm of calculation and estimations for various ecosystems on CO_2 sink/sources from view point of plant biomass increment is essential. We also discuss the ability of application to develop afforestation on a desert region by using biotechnology.

Lastly, development of functional materials is essential. For a cancellation of accumulated salt on the soil surface, we will try to use sand-soil as an experimental material because clay accumulates salinity more than sand-soil. The material which makes the impermeable layer in the soil by use of polyacrylic acid has been developed. Polymer decreases the hydraulic conductivity of soil and increases the water holding capacity in the soil. We are able to control the depth of the impermeable layer by using the combination of sodium and calcium. We can easily make condensed water at the rate of 3 liter per m^2 a day by use of solar energy and vinyl-film.

4) Technological problems in systems approach of greening

There are many technological problems in the greening of arid and semiarid land, especially in the field of systems approach. Many problems in this region have not been studied. It is difficult for us to even define the content as well as the border of the research subject. Thus, we focus on the following two subjects as the problems which confront:

(1) Construction of an ecological model for greening of arid and semiarid land: Ecosystems in general have a constant flow of circulating materials which stem from the interactions between the soil, flora, fauna and microorganisms, and maintain a dynamic equilibrium. Since desert greening is a project for constructing an ecosystem centered on a plant community, gaining an quantitative understanding of the flow of circulating materials in a desert greening ecosystem is an important task which must be carried out first, not only to assess the stability of the system but also to examine the strategy of the greening project. However, the academic and informational records in this area are poor, and in particular, there are no available models of circulating materials in desert greening ecosystems.

To be concrete, we should obtain at first existing data related to the flow of materials such as water, carbon, nitrogen, phosphorus, minerals, etc. circulating in the course of the various activities of plants (trees, crops, pasture, etc.) and animals (cattle and feral animals such as birds, etc.) as well as soil micro-organisms. We can then quantify the amount of circulating materials in a greening ecosystem. With this as a basis, we try to construct a model which can simulate the changes in the ecosystem as the greening project progresses. This will incorporate data provided from greening area to clarify the items which need to be measured on-site.

In the next step we should computerize the ecosystem simulation model and develop it to the stage where it can simulate the changes in the ecosystem due to the progress of the greening. With incorporating on-site observations into the necessary kinetic data, etc. we will simulate the changes in the ecosystem on this basis and consider the suitability of the model by studying how well it reproduces actual changes in the ecosystem. For each greening technique (and strategy) which is used, we should apply the ecosystem simulation model to every possible case with altered initial conditions, boundary conditions, etc. In particular, we can consider by the model the choice between energy intensive and ecological technology, or the optimum combination, from the aspects of the rate at which a green ecosystem is constructed (that is, the efficiency of the method) and the stability of the ecosystem.

(2) Establishment of a method for balancing energies in desert greening: For assessing the net amount of fixed carbon dioxide due to greening, we must calculate the net amount of carbon dioxide which is fixed by the forest by subtracting consumption by absorption, periodic thinning, leaf shedding, etc. from the initial quantity fixed by photosynthesis. Apart from this, we must also consider the carbon dioxide generated by the raw materials and utilities, water supply, etc. to make the various materials, solar cells, factories, etc. which are invested to promote the greening project. In addition, we must choose between energy intensity and ecological technology or find the optimum combination and, in order to make an equitable assessment of the quantity of energy invested and its effect, an accurate quantification of energy input to and output from the desert greening system is mandatory. Therefore, solar energy and its net fixed amount and the quantity of the various invested artificial energies must be modeled with the utmost detail and accuracy, and assessment coefficients in respect of the net amount of fixed carbon dioxidemust be produced in a practical form.

In the first step, we should prepare and model the measurements and calculations which will be needed in order to quantify solar energy and its net fixed quantity and the various artificial invested energies. Since this will necessitate knowing the basic energy units invested in water creation, solar cells, irrigation methods and various other materials, an energy data base will be constructed in order to calculate the energies in each of the relevant technologies.

In the second step we should computerize the energy balance model and develop it to the stage where simulations can be made. We use the model to calculate the energy investment required in the whole ecosystem when various greening techniques are applied to the desert greening system. From this, and the amount of fixed solar energy derived from the model of ecosystem greening, we can obtain the net carbon dioxide fixing effect. And then, for each technique and greening strategy, we use the energy balance model which has been constructed to quantify the degree of dependence of the net carbon dioxide fixing effect on the invested energy, calculating over periods of one to ten decades, with time as a parameter.

4. Methodology to Evaluation of Effects of Greening on the Carbon Dioxide Problem

The detail evaluation method, future approach and prospective are explained in the present part. With the increased energy input, the amount of fixed carbon is expected to be drastically increased, and, attain plateau as shown in Fig. 5. It can be shown that there

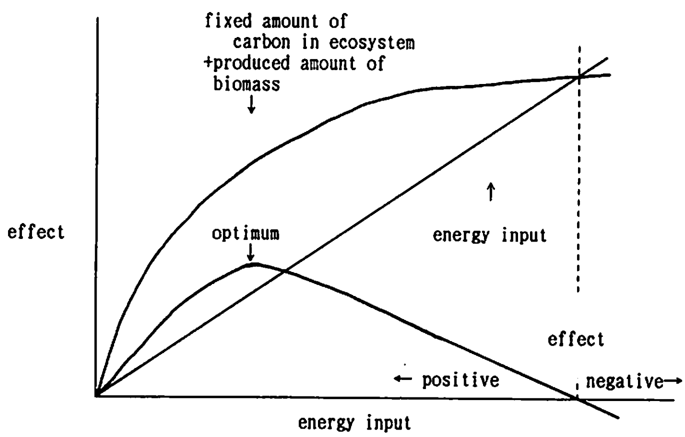

Fig. 5. Effect of energy supply on carbon balance.

exist optimum energy input.

For the evaluation of the net fixation the energy input should be subtracted from the amount of fixed carbon. The important evaluation functions we proposed are shown in the following. Time range for this estimation is supposed to be one hundred years, however, the term of valuation itself is one of variable parameters for estimation.

We are to evaluate afforestation techniques using equations given as follows;

(1) Energy balance (per unit area), E

$$E=(C-C_0+B-I)/I$$

where C is average amount of carbon fixed in ecosystem during the period of hundred years (the period, n year, is also a parameter), C_0 is initial amount of carbon in ecosystem, B is amount of carbon accumulated as a result of biomass production, I is artificial cumulative energy input to the project. To realize the net carbon fixation, positive value of the equation is necessary. The higher value means the more stable measure. The higher value of the numerator means the more effective one.

(2) Contribution, K

$$K=A/[(C-C_0+B-I)\times S/n]$$

where A is average amount of carbon accumulated in air, and S is total area of arid land suitable for afforestation.

(3) Man power (per unit area), M

$$M=(T\times A\times n)/[(C-C_0+B-I)\times P]$$

where T is average number of staffs necessary for the project and P is present population in the world.

In the present study, after the primary evaluation is conducted for various measures using carbon fixation by plant, the experimental studies are conducted for afforestation of arid land.

By conduction of the present research including the elemental and field tests, the reasonability of individual techniques is elucidated. The validity of the total system is evaluated, *i.e.*, the contribution of the technique to the carbon dioxide issue and the possible area to be used are clarified.

Finally, we plan to evaluate energy required for the countermeasures and propose the most effective definite plan for total system consisting of energy production, salt removal, water supply and afforestation. The optimization of the system of this measures is to conducted, which leads to the direction of future research. The present results also contribute to the international common recognition of importance of afforestation and focus on Japanese contribution in this issue.

5. Summary and Conclusion

In the present paper, first, the important role of greening of arid and semiarid lands in the carbon dioxide problem was demonstrated by showing the data on carbon cycle and stock in this planet.

Second, a project to assess the above possibilities, conducted under the sponsorship of RITE, Research Institute of Innovative Technology for the Earth, and The Japan Gas Association was introduced. The activity of the project was explained and future approach and prospective were discussed.

Third, the methodology of the evaluation of the effects of the greening on the problem was presented.

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Reclamation of Open Pit Mining Spoils in Temperate Desert Environments

James A. Young*, Robert R. Blank* and William S. Longland*

1. Introduction

The mining of precious metals in the state of Nevada is annually a 2.8 billion dollar industry. This 20th century gold and silver boom is the result of the discovery of deposits of microscopic sized precious metal and the development of technology to economically recovery these materials. During the 19th century pioneer miners and their burros walked over the vast microscopic precious metal deposits without realizing they existed. The gold was too small to be seen in the traditional miners pan. It was just as well the 19th century did not recognize the fine gold because the concentration of the precious metals is so low that vast amounts of ore have to be excavated for recovery and no method existed for the concentration of the microscopic gold and silver.

The 19th century miners searched for gold and silver concentrated in veins in hard rock. The exploitation of such deposits was by underground mining. The ore was raised to the surface, crushed in stamp mills, and the precious metals amalgamated with mercury.[1] This was a very inefficient procedure with recovery rates of 60 to 70% being common.

In the 1890s the use of the MacArthur-Forest process was introduced. A diluted solution of cyanide was used to dissolve precious metals in finely crushed ore, with recovery accomplished by precipitating on zinc shavings.[2] This process was so much more efficient than amalgamation that virtually every earlier mine dump in the western United States was re-worked for cyanide treatment. Hard rock gold mining was declared a non-essential industry in the United States during World War II and was discontinued by governmental regulation. After the war, the fixed price of gold in the United States and the high labor cost of underground mining combined to severely limit the rebirth of the industry.

In 1967 the US Bureau of Mines conducted an engineering appraisal of more than 1,300 lode and placer deposits, representing almost all of the United State's known gold reserves, to determine their potential gold production.[3] These deposits were estimated to contain over 400 million ounces (we retain ounces instead of metric measurement because of international use of ounces with precious metals) of gold. However, only 2% of these deposits were exploitable with the price of gold standardized at $35.00 per ounce. Within the next two years the price of gold was allowed to float freely on the world market and a 400% price increase changed the definition of what constituted economically exploitable ore.

The rapid rise in the value of gold once the price was allowed to float freely on the international market, sparked renewed interest in gold and silver mining. At the same time, a number of technological factors coincided to make it possible to exploit vast deposits of low value ore and economically extract the precious metal content. The first of these technological advances was the continued development of large self-propelled, rubber-tired mechanical equipment for moving large quantities of rock. This started late in the 19th century when the first steam powered shovels were nearly simultaneously delivered to the Bingham, Utah and Ruth, Nevada copper pits in the western United States and to the pre-historic gold and silver mines at Rio Tinto in Spain. All-wheel-drive, articulating front-end loaders capable of loading a 20 yard dump truck with one bucket are the culmination of technical evolution from these early railroad track bound steam shovels.[4]

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The second coinciding branch of technology that matured in the 1960s involved changing the way cyanide was used to dissolve the precious metals in ore. The cyanide process evolved from the stamp mill to roller or ball mills so that the ore could be ground extremely fine. The precious metals had to be in very small particles for the cyanide to dissolve them in an economically feasible period of time. The finely ground ore was hydraulically moved into tanks where the cyanide solution was leached through the ore to dissolve the metals. The physical infrastructure necessary to carry out this process and the labor required were considerable.

After World War II there was a tremendous boom in the mining of uranium in the western United States as the world moved into the age of atomic weapons and energy sources. Some miners experimented with heap leaching of low grade uranium ores in an attempt to concentrate economically recoverable values. This was an extension of an ancient process used in copper deposits where acids were used to concentrate copper values. Several scientists at the United States Bureau of Mines research laboratories at Salt Lake city, Utah, and Reno, Nevada extended this technology to gold recovery from low value ores.[5] The process is very simple. The ore is piled on an impervious surface and a very dilute solution of cyanide is sprinkled over the surface and allowed to peculate down through the pile. The solution is collected from the impervious surface and when sufficient value in precious metals is accumulated they are precipitated and the cyanide solution returned to recycle through the pike.

The initial experiments were conducted on a sheet of plastic in the parking lot of the Federal Bureau of Mines in Reno, Nevada with a few buckets full of ore. The process has now progressed to the point heap leach piles cover several hundred hectares to a depth of many meters. Some of these piles hold as much as 35 million liters of cyanide solution.

The factor that made this heap leaching technology so successful in Nevada was the simultaneous discovery of huge reserves of microscopic sized gold and silver deposits. Among the first of the large operations to exploit the deposits of microscopic gold was the Carlin Mine located in northeastern Nevada. It began production in 1965 with an estimated ore reserve of 9.9 million tons (metric) averaging 0.29 ounces of gold per ton. The mine eventually produced 3.2 million ounces. The Carlin Mine was located on what became known as the Carlin Trend. The Carlin Trend of microscopic gold deposits are hosted in a series of Silurian-Devonian rocks of the Roberts Mountain Formation that are exposed in a tectonic window by thrust faulting.[6]

Environmental setting

This modern mining boom has taken place in a temperate desert environment. Most of the mines occur on lands which formerly furnished forage and habitat for domestic livestock and wildlife. Most of the land is publicly owned and administered by agencies of the American federal government. The rise in ecological awareness among the general public has quickly focused on the need for reclamation of desert lands disturbed by open pit mining and heap-leach recovery of gold and silver.

Federal, and more recent state regulations, require that miners must post a bond sufficient for the reclamation of lands disturbed by the mining process. For large mines, these bonds total in the tens of millions of dollars. These bonds will only be released when the reclamation process has been judged to be a success. Apparently, no precious metals mine in Nevada has been released from reclamation bonds to date.

Until recently it was considered impossible to reclaim mine waste in a desert environment in the United States. Faced with specific federal regulations and an aroused public, the precious metal mining industry has undertaken serious efforts to develop reclamation procedures for temperate desert environments. As a part of this effort, the Conservation Biology of Rangelands research project of the USDA, Agricultural Research Service, Reno, Nevada was commissioned to review current reclamation projects and evaluate future research needs.[7] Much of the information reported in this paper had its origin in information gained and observations made during that review.

3. Determining the Goals of Mine Reclamation

To be successful, mining reclamation needs to have clear goals and priorities. In a desert environment this is especially true. When agricultural land is strip-mined for coal in the humid eastern United States, regulations require a pre-mining sampling of crop production with reclamation efforts having to at least equal some predetermined amount of that production after mining. During the energy crisis of the 1970s strip mining of coal moved to the northerm Great Plains where huge deposits of low sulphur coal existed. The same reclamation goals were followed with generally disastrous results for rangelands. Many of the premining rangeland communities were in poor range condition because of past improper management. Essentially the standards required restoration of communities producing desired biomass at a fraction of their potential.

The desert rangelands of the Great Basin are an even more extreme example of this problem. In the 1960s it was determined that in the Humboldt River Basin of northern Nevada only 1% of the 6 million hectares of big sagebrush (*Artemisia tridentata*)/bunchgrass rangeland was in good range condition, the rest was in poor to terrible condition.[8] During the 20th century the alien annual weed cheatgrass (*Bromus tectorum*) has invaded millions of hectares of degraded rangeland in the Great Basin.[9] Obviously, the goal of mining reclamation should not be to create more degraded habitat.

Among the criteria that should be considered in planning a reclamation project are: a) protect the site from accelerated erosion, b) inhibit the invasion by alien weeds, c) return the site to basic productivity, d) blend the reclamation project into the surrounding landscape, e) insure the reclamation project does not unduly influence biodiversity of the surrounding ecosystems, and f) accomplish all of these goals economically. Miners, ranchers, wildlife managers, and environmentalists would probably include all of the above in their goals for reclamation, but each might assign different priorities to the list. Consensus may be difficult to obtain, but it is very important that a clear goal be established before planning the reclamation project.

1) Types of reclamation sites

The types of sites that exist that require reclamation are the excavated pit, waste rock dumps, heap leach pads, and exploration areas. In Nevada exploration sites are estimated to constitute two thirds of mining disturbance requiring reclamation. We will develop this more in a later section. In Nevada the excavation pits are not reclaimed at this time. There is not a lot you can do about the pit except refill the hole. The rock cut surfaces will not support most vascular plants. The pits constitute long term hazardous sites that have to be excluded from public use. They are radically different in appearance from surrounding landscapes. In other states with less extensive mining activities, miners have been required to refill the pit but, Nevada miners strongly protest that pit refilling is not economically feasible. Some mining companies have paid for off-site reclamation or restoration projects in lieu of reclaiming a pit.

In Nevada some leach pads are in the final stage of rinsing, but no large scale leach operations have progressed sufficiently to enter the reclamation process. Over time the cyanide converts to nitrate. The nitrogen rich pads with relatively fine-textured ore are quality sites for plant growth. Weed control is often necessary on the pads because organic matter interferes with the precipitation of the precious metals from the cyanide solution. Eventually many hectares of leach pads will require reclamation. What to do with the nitrogen rich rinse water may be a larger problem than establishing vegetative cover.

The major reclamation problem on the mining sites is the treatment of waste rock dumps. These dumps are built by rear dumping trucks which drop rock at or over the edge of the dump. Most mining plans require that dumps are built with slopes much less than the angle of repose for the material.

2) Reclamation Of exploration sites

As previously mentioned, mineral exploration disturbance accounts for two thirds of the area requiring reclamation in Nevada. Determining the extent and nature of vast deposits of low concentration ores requires a lot of samples obtained by drilling. Traditional truck mounted exploration drills require access roads. It is the nature of exploration disturbance to be linear and to effect only a small fraction of the surrounding landscape. Typically 10 ha would require reclamation in a 1000 ha rangeland pasture. More than one mining company may explore the same mineralized area. There are mineral prospects in Nevada that have been explored and reclaimed three times.

Technological developments to limit disturbance from exploration of mineral prospects include self-propelled drills with flotation tires to lessen the need for roads. A more novel approach is to delineate mineralized locations by analyzing plant material for precious metal content. A problem with applying this technology is false positives from subaerial deposition of microscopic gold and silver on leaves.

The linear nature of exploration disturbance enhances the chances for spontaneous natural seedling recruitment from adjacent vegetation if the road is re-contoured and a seedbed properly prepared. On the minus side, the linear nature of the disturbance means the seedlings in the reclamation project are exposed to predation from large and small herbivores. For domestic livestock, the reclamation seeding can be coordinated with grazing management systems that usually include a year of rest from grazing. For wildlife and free roaming equine species, other approaches to reducing predation may be necesary. One suggestion has been to plant species *not* preferred by native herbivores. Termed aversion seeding, this procedure is slow to gain popularity because it is philosophically counter to the concept that reclamation seeding results in quality forage species.[10]

3. Reclamation of Waste Rock Dumps

The key to successful reclamation of mine spoils in temperate desert environments has proven to be providing a suitable seedbed and seedling environment. The conservation and management of top soil is crucial for providing an adequate seedbed.

1) Top soil management

In an arid environment where soil development is very limited, the term top soil is rather misleading. It is more of a question of conserving the more or less fine textured surface material for re-spreading once waste rock dumps are re-contoured. Little is known about the biological conservation of top soil under desert conditions. Should it be planted with a cover crop to maintain soil micro-organisms? There is little direct experimental evidence that is applicable to the environmental setting. We noted that virtually every top soil dump was covered with the weeds Russian thistle (*Salsola australis*) and halogeton (*Halogeton glomeratus*). Mines that excavate through alluvial fans, which are so characteristic of basin and range topography, often utilize fossil soils they find buried in the fans, as top soil.

2) Re-contouring

How well the reclamation project blends in with the surrounding landscape is largely a product of how well the waste rock dumps are re-contoured. Some mines are extremely proud of the re-contouring efforts they have made. Moving large volumes of rock and soil is what open pit miners are equipped for and experienced with so it is not surprising they are often very successful with such operations. Mines usually spend 10 times as much on physical operations in reclamation as they do in biological operations. Most of this money is spent on re-contouring.

Besides appearance and stability, the re-contouring operation also has a major impact on what options are available for seeding waste rock dumps. For safety, earth moving equipment in re-contouring works up and down slopes. Water control structures and seeding should be done on the contour. Some of the mines most successful in mine reclamation have the same foreman and crew conduct both re-contouring and seeding. The obvious self interest in not making slopes to steep for contour seeding has proven very successful.

After re-contouring the stock-piled top soil is spread over the dump. This is usually done with self loading carryall scrapers. These implements operate on immense flotation tires, but their great weight often compacts the surface horizons. The last step in the re-contouring-top-soiling process should be ripping the surface to return some form of structure.

3) Seeding mixture

The supervisors of mining reclamation projects in the precious metal mining industry in the temperate deserts of North America, are usually geologists, geological engineers, or environmental engineers. These largely non-biologist reclamation specialists are faced with an array of conflicting advice and criticism on what to seed on the mine dumps. Should only native species be used to protect biological diversity? Should the very best in forage species be planted? What species are being included for wildlife, native plant enthusiasts, or amateur butterfly clubs.

The people in charge of making the selection do not understand the highly complex governmental and private systems under which plant material for conservation plantings is developed, propagated for increase and distributed in commercial marketing in the United States. Most of the supervisors have never seen the plants they are planting and would not recognize them if they grew.

The lack of biological knowledge often leads to very expensive, multi-species seeding mixtures where the members of the mixtures are mutually self canceling. That is, if species A did happen to be adapted it is almost automatic that species B will not be adapted because of inherent, sharply contrasting ecological requirements. A time proven rule-of-thumb for perennial grass stand density has been in the 25 to 30 cm precipitation range of the big sagebrush (*Artemisia tridentata*) zone of the Great Basin a fully stocked stand has 7.5 plants per m^2.[11] Commonly reclamation seedings are made at the rate of 1,500 to 2,000 pure live seeds per m^2. These seeding rates only provide expensive, ineffective mulches.

To biologically suppress the competition posed by invading alien annual grasses, the seeding mixture must contain a vigorous perennial grass. For long term sustainablity the mixture should contain an adapted shrub. For diversity the mixture should contain a perennial forb. Adding repeated selections or cultivars of often very closely related plant material to the mixture is biological redundancy, not diversity and often results in excessive inter or intra-specific competition.

4) Seeding equipment

In an arid environment where moisture is out of phase with temperatures for plant growth, the moisture gradient from a seed on the surface of a seedbed to the atmosphere is usually inhibitory for germination.[12] Seeds have to be placed in the surface of the seedbed and the seedbed firmed to enhance hydraulic conductivity from the substrate to the seed coat. This means the seeds have to be placed in the seedbed with a planting drill. Drills are a standard part of agronomic agriculture, but to function on mine dumps they require considerable specialized engineering.[13] For the waste rock dumps to be seeded with a drill the re-contouring has to be within limits that permit a track laying tractor to move on the contour of the slope.

5) Irrigation

If the primary form of plant competition that limits seedling recruitment is for moisture, it would appear logical that supplemental irrigation may enhance reclamation success. Many of the mine pits have progressed well below the water table and dewatering is a major operation. The miners sprinkle many hectares of leach pads with cyanide solution applied through modified irrigation sprinklers or drip systems, so they should be familiar with the technology. Logic and biological realism often clash in desert environments. Many of the hybridized and selected plant cultivars used in mine reclamation do not have the inherent potential to prosper under supplemental irigation. Many of the native plant species that are collected for use in mining reclamation are killed by supplemental irrigation.

There are many examples where supplemental irrigation has led to successful reclamation efforts in temperate desert environments. Perhaps universally these successful efforts have involved someone directly in the operation who understood the biological moisture relations of the plants used in the reclamation seeding. It is well to remember that irrigation also fosters agricultural weeds on the mine site.

6) Fertilizers

Temperate desert ecosystems revolve around competition for moisture available for plant growth, but it has long been recognized that available nitrate is the catalyst that governs this competition. Because most reclamation seedings are dependent on rain fed moisture it is very hard to predict if a supplemental source of nitrogen will help or hinder seedling establishment.

4. Salt Desert Environments

The most difficult sites in temperate deserts to reclaim through reclamation of mine spoils are those located at low elevations in the desert basins. These areas are commonly referred to as salt deserts because of the accumulations of soluble salts in the soil. On the upper alluvial fans where many of the mining operations are located, extreme salt affected soils are not the common problem. The extreme aridity of the sites makes artificial recruitment of seedlings very difficult.

A major problem with reclamation seedings in these environments is a lack of adapted plant material. Miners are reaching out for native plant material which appears obviously adapted to such sites. Unfortunately, natural seedling recruitment may be extremely episodic in such environments. The need to conserve and develop native plant material in such sites is great.

5. Summary

Since time, immemorial miners have dug for silver and gold and left the holes. As the worlds population increases, greater value is placed on numerous aspects of wildlands. The deserts of western North America have immense treasures of exploitable precious metals, but society demands that mining spoils must be reclaimed and made acceptable parts of the surrounding landscape. The biological processes involved in seedling recruitment in desert environments are extremely challenging to scientists, but most problems can be overcome. Communicating this biological knowledge to the technical people who actually carry out the reclamation is also a challenge to scientists.

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Design of the Integrated Renewable Energy System for Oasis

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Absoract

Desertification is a serious environmental problem in the world. Many efforts have been made to prevent it but no remarkable results have been observed yet. In order to stop the desertification, the authors are considering to enrich living spaces in the oasis and enable a lot of people to live there. This requires us to provide various kind of resources such as water, food, particularly energy and power. This paper aimed to propose a new energy system in an oasis, namely, Integrated Renewable Energy System (IRES) and to evaluate the feasibility of it.

1. Introduction

What kinds of energy sources are available and feasible to meet the energy demand is a critical factor when we design an oasis. There are studies which have considered the energy system at an oasis or in remote areas from view point of reliability and economics. Meanwhile environment protection and better ecological circulation should not be neglected.

The concept of integrated renwable energy system (IRES) for desert oasis is based on the idea of considering not only system's reliability and cost but also environment conservation and good ecological balance. In this system, all kinds of energy sources are renewable to get ride of the emission of harmful gases (*e.g.*, CO_2, SO_2, NO_X) and solid waste disposal (*e.g.*, radioactive waste), and to create a harmonic environment which enable us to co-existence with natural environment. It is shown in Fig. 1 that IRES is constructed by energy supply system and energy demand system. The energy supply system consists three subsystems—energy sources subsystem, energy transfer one and energy storage one. Every subsystem has its own functions and relates each other closely.

IRES can combine advantages of various energy sources and overcome their disadvantages. Details of comparisons of single renewable energy system, integrated renewable energy system and integrated system of renewable and conventional energy, and how IRES can meet energy demand with high reliability and reasonable cost will be discussed respectively.

For the new settlement in desert area, this paper will discuss the general scheme for optimal utilization of several renewable energy resources as an integrated system to meet various load demands. The integrated sources are solar thermal power plant, PV power plant, solar pond, wind mill, biogas generator, together with different types of storage facilities (electric and fresh water storage).

2. Natural Conditions and Energy Demand in Oasis

In desert areas, the hot and arid climates are characterized by high temperatures during daytime and low temperatures during the night, intensive solar radiation, low relative humidity. The rate of evaporation exceeds the rate of rainfall. This results in a shortage and scarcity of potable water. Out door conditions are so critical in this climate that both the buildin'g and it's external living spaces must be protected from daytime intense solar irradiation and hot winds, and nighttime cold weather.[1] Therefore, two most important as-

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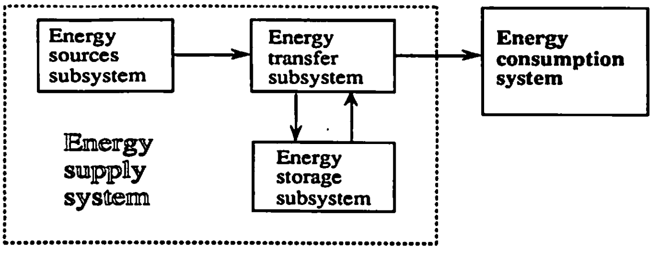

Fig. 1. System structure.

pects in desert are water and comfortable living conditions that include sunlight, suitable temperature and ventilation not only for human being but also for animals and plants.

The energy demand in oasis can be divided into four branches. They are agriculture (which mainly consists of farming, stock raising, forestry, agricultural production processing and so on), water resources, industry and merchandise, daily life respectively.

3. Energy Supply System

1) Different energy systems

Usually, there are two types of different energy supply systems in small scale for desert and remote areas. One is single renewable energy system.[1,2] It has a larger power capacity and storage volume for power storage and regeneration than the volume of load to keep the system reliable, because this system just has one energy source which can not be transferred into usable energy form such as electricity continuously (*e.g.*, solar energy can not be used in night and rainy days, wind mill depends on a certain rage of wind speed). Typical type of this kind of systems is one of PV power, solar thermal power and wind power combining one of storage batteries and fuel cells.

Another is integrated system of renewable energy and conventional energy sources.[3] Comparing with single renewable energy system, it has two or more than two energy sources to generate power. In this case, energy storage subsystem's volume can be decreased without reducing reliability. Some of this kind of systems consist one renewable energy source, one conventional energy source and one storage subsystem (*e.g.*, solar thermal power or PV power, diesel or natural gas and storage subsystem; wind power, diesel or natural gas and storage subsystem). The others are composed by two renewable energy sources, one conventional energy source and one storage subsystem (*e.g.*, PV power or solar thermal power, wind power, diesel or natural gas and storage subsystem; PV power, solar thermal power, diesel or natural gas and storage subsystem).

Integrated system combining different energy sources, especially more than two energy sources' system, can take the advantages of the individual sources in a complementary way in order to supply power more effective. First, this makes it possible to install a lower level of peak power as compared with a non-combined system. Secondly, battery capacity can be smaller as the probability of continuity of supply increases.

Obviously, integrated system of renewable energy and conventional energy is better than single renewable energy system. Considering the environment protection, biomass energy should be introduced into energy system instead of fossil energy as a auxiliary energy of the system. Biomass energy can be used for cooking and supplementary source of power generation, and its potential is abundant and easily obtained from crop's straw, human and animal excreta and fire wood in oasis. Usually, biomass is ignored or used with lower efficiency.

In comparison with fossil energy sources, biomass energy has its special features. First of all, it is renewable energy. It does generate CO_2 and consume O_2 when it is used to generate power. But, plant absorbs CO_2 and release O_2 during the biomass forming through photosynthesis. So the net production of CO_2 is zero. That means CO_2 and O_2 balance can be kept by biomass itself. Fossil energy sources don't have this function. In addition, the emission of SO_2, NO_X from biomass energy is less than that from fossil energy. For example,[4] it generally contains less than 0.1 percent sulfur and to 5 percent ash, compared with 2 to 3 percent and 10 to 15 percent, respectively, for bituminous coal. Secondly, some of the raw materials of bioenergy are from waste materials, for example, human and animal wastes, some kinds of sewage, and straw are essential raw materials in the methane gas production. Side line production of biogas is the high quality organic fertilizer for farming and good fodder for animals. So, biomass plays a very important role in ecological circulation.

As discussed earlier, according to the natural conditions in desert, solar energy and wind energy are rich enough to be used as main energy sources. Therefore, the integrated renewable energy system combines solar energy, wind energy and biomass energy.

2) The energy transfer technologies

In recent years, renewable energy application for power generation is widely spreaded in the world. Using different kinds of energy sources and different application forms have different features.

In desert, solar energy is the main energy source of IRES, as it is much more abundant than that in other areas. Solar thermal power plant can be built in a large scale (prospective capacity is about 150–200 MW and present scale is 80–100MW) and has a relative high efficiency. Solar thermal power plant can cogenerate both electricity and thermal energy. The waste heat exhausted from turbine can be reused for three different purposes with different ranges of temperature. The first is for brackish water desalination. Salted water can be heated at more than 100 centi-degree for evaporation; The second is for air conditioning and refrigeration. The heat media can be heated at about 80 centi-degree; The last is for hot water supply. The water can be heated at about 50 centi-degree. The ratio of heat to electricity in cogeneration system generally is more than 1 : 1. Obviously, it is the best option to supply both electricity and Thermal energy efficiently. Solar cell directly converting solar radiation to electricity by photovoltaics has some significant advantages such as silent and minimum maintenance. A special feature is that solar arrays are made up of multiple solar cell modules, they can therefore be made in a range of sizes for a wide and variety applications with essentially the same conversion efficiency and the same technology. For example, the solar cell of a 1 mW wrist watch and a 1 MW PV power plant can be operated with same transferring efficiency.

Under favorable circumstances, the cost of wind energy is already lower than that of conventional energy system.[6] Expected capital cost reductions will further increase the comparative advantage of wind system and will improve the prospects for energy from other renewable energy sources in the competition with conventional sources. Biomass energy not only can provide electricity and heat, but also has the ability to keep ecological balance and to change waste into valuables. The cost of power generation is relative low.

Generally speaking, the cost of the power generation from renewable energy is expected to rapidly decrease while that from conventional sources will be steady or will increase. In recent report,[5] the cost of a 80 MW solar thermal power has dropped to 7–8 U.S. cent/kwh. If environmental costs were added to the calculations which for fossil and nuclear energy can be 20% or more the competitive factors in renewable energy power would be more apparent.[6]

3) Energy storage technologies

Energy storage subsystem plays a very important role for high reliability of IRES. For electricity storage, the following methods are feasible and effective.

A. Storage batteries

There are many different kinds of storage batteries have been developed. Na-S, $Zn\text{-}CL_2$, $Zn\text{-}Br_2$, Redox-flow are main four types storage-batteries system which are used commonly nowadays.

B. Biogas storage

The first task of biogas is to satisfy heat demand for daily cooking. The remainder can be stored if solar and wind energy can provide

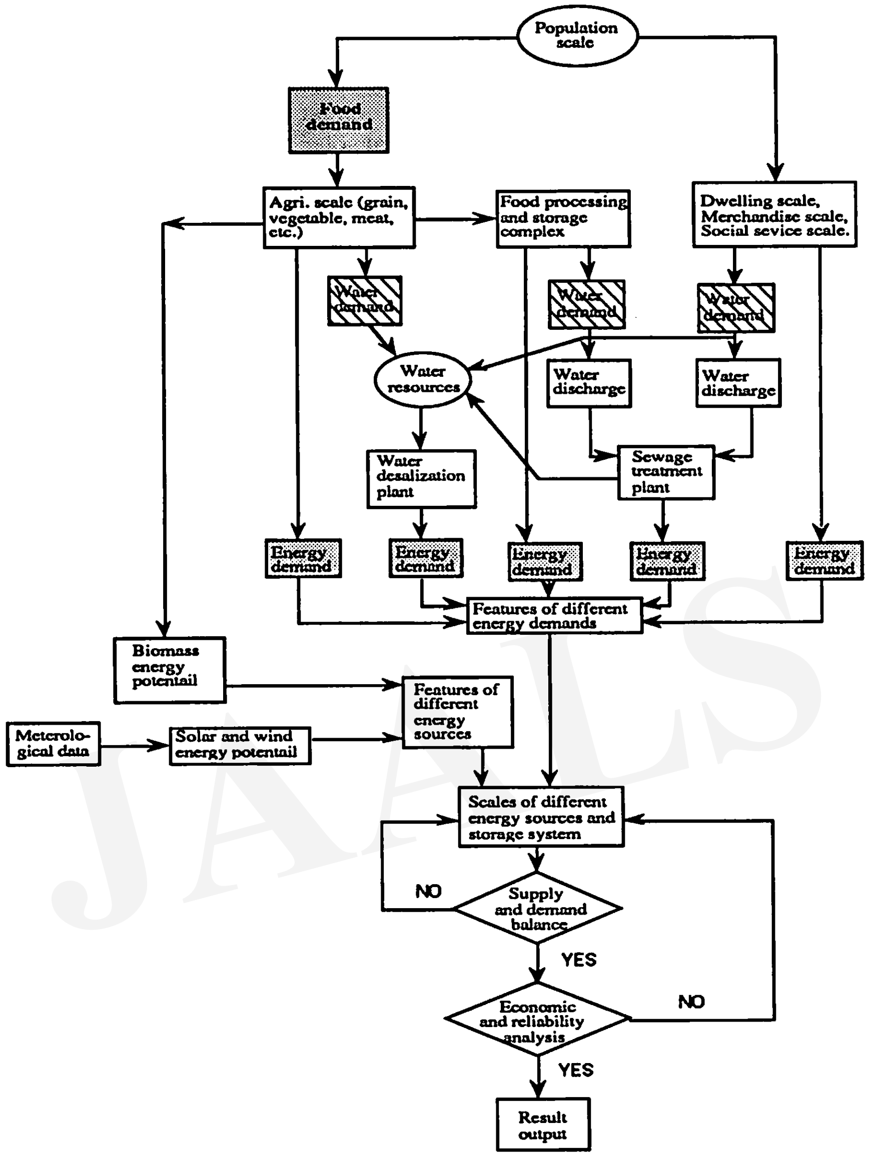

Fig. 2. Design steps of IRES.

sufficient energy to meet the load. There are two ways to use biogas for power generation. One is that use it as an auxiliary energy to assist solar power maintaining certain output of thermal energy for power generation when insolation is not strong. Another is that use it generate power directly whenever it is needed.

C. Fresh water storage

Fresh water storage is a good and indirect way to store energy from renewables when energy supply is greater than energy demand. It will reduce the load of energy demand when renewables can not supply enough energy for water desalination.

For thermal energy storage, there are many facilities with different materials in both sensitive heat form and latent heat form to store thermal energy. Solar pond, as a thermal collector and thermal storage, should be built. The most important reason is that solar pond is a suitable and safe container for the disposal waste water (brine) in desalination processing, and in turn the brine will breed salt gradient of solar pond.

Figure. 2 shows the designing steps of the IRES has been set up according to the basic considerations of high reliability, reasonable cost, environmental protection and ecological balance.[7,8,9]

4. Oasis Scale, Water Demand and Energy Demand

After the population of the oasis being decided, the scale of agriculture, industry, merchandize, and the others can be calculated. In this design, assume that industry includes food processing and storage complex, water treatment plant, water desalination plant, and renewable power system. Agricultural scale is structured on the basis of food self-satisfaction, according to the population scale.

To calculate water demand for agriculture and other expenses and energy demand for oasis, water resources should be well known in the oasis, *e.g.*, depth of underground fresh water and brackish water, annual amount of fresh water, rainfall, evapotranspiration and percolation.

(1) Water demand for agriculture

(2) Water demand for others

Excluding water demand of agriculture, the daily water demand for other purposes includes industry, daily life and merchandise.

(3) Water discharge

In order to save limited water resources in desert, the discharged water should be reused for agricultural irrigation after that sewage is treated.

Energy demand for various purposesis listed below.

(1) Energy demand for agriculture

A. Field crop production

B. Greenhouse

C. Stock raising

(2) Energy demand for domestics

A. dwelling

B. Office

C. Hospital

D. Merchandize

E. Other social services

(3) The energy demand of industry

A. Food processing and storage complex

B. Water desalination

Water desalination can be realized by using different methods. In this design, MSF (multi-stage flash) plant (which mainly using thermal energy by means of evaporation and using small amount of electricity) and RO (reverse osmosis) plant (which using electricity to separate fresh water and brine) will be used.

a. MSF plant

b. RO plant

C. Water treatment

(4) Energy demand of water resources

The fresh water in desert comes from two sources (excluding rainfall). Those are underground fresh water and fresh water from desalinated underground brackish water or seawater.

Features of loads for various usages are different.

a. Some of loads change in different seasons or months. But these loads can be met in any time period within one day or one month. In another word, the hourly load is not constant. if the total amount can be met within one day or one month. So, these loads can be arranged when energy output from renewables is bigger than the energy demand of loads which are certain amount at certain time.

b. Some of loads don't change or change a little in different seasons or months. But These loads change largely in different hour during a day. Hourly requirement for those is fixed. This kind of loads can not be arranged.

c. Some of loads can be met by one of electricity and mostly by thermal energy. This kind of loads can be used for adjusting thermal and electricity balance. In this design, water desalination by MSF plant and RO plant will be used for this aim.

5. Renewable Energy Resources

In this system solar energy, wind energy, and biomass energy will be utilized to meet the energy demand in the oasis. Potential of solar energy and wind energy can be calculated by natural conditions of oasis. Potential of biomass energy can be calculated by the scales of population and agriculture.

Features of renewable energy

In order to meet the energy demand efficiently, Features of three different kinds of energy sources should be studied. Solar and wind energy are usually variable comparing with conventional power sources. But, They often directly complementary. In Thermally-driven wind regimes, the strongest wind may occur towards or after sunset, and sometimes strong wind tend to be associated with overcast condition. It will increase the reliability of power supply system. Another point is that some loads' variations strongly depend on the solar radiation especially in desert areas. For example, load of air conditioning and agriculture will increase when sunshine is sharp. Meanwhile, power output from solar energy will enhance too. Coincidence of load and energy supply will be helpful to decrease the capacity of storage system. Power output from biomass energy is more stable than that of solar and wind energy. It has some advantages. First, it can be stored easily; Secondly, it can be used whenever it is needed such as solar and wind energy can not provide enough power to meet the demand; The third is that it can provide both electricity and thermal energy. Consequently the combination of solar, wind and biomass energy will make the power supply system more reliable.

6. System Simulation

1) The scales of renewable energy and energy storage.

The balance between annual output of electricity and thermal energy from renewable energy and annual energy demand can be estimated as:

$$Ep\ Kep \geq Ed$$
$$Ep = Ast\ Pst + Apv\ Ppv + Aw\ Pw + Pbe$$
$$Tp \geq Td$$
$$Tp = Ast\ Hst + Asp\ Hsp + Hbh$$
$$Ed = Efix + Evar$$
$$Efix = Ea + Ec + Eif + Eit = const.$$
$$Evar = Eid1 + Eid2$$
$$Ep = Ast\ Pst + Apv\ Ppv + Aw\ Pw + Pbe$$

As mentioned above, $Eid1 = f(Ast)$, Eid1 is a function of the scale of solar thermal power, then, it becomes:

$$Kep(Ast\ Pst + Apv\ Ppv + Aw\ Pw + Pbe) \geq f(Ast) + const.$$

Energy storage can be realized by indirect way and direct way. In this design, storage batteries and biogas are direct ways to store energy. Storage of fresh water desalinated from brackish water or sea water is the indirect way to store electricity and thermal energy. Because it consumes energy when energy supply is greater than energy demand, and can be used when energy supply is less than the energy demand to save the energy supply for desalination of that amount of brackish water or sea water. Obviously, the cost of biogas and fresh water storage is cheaper than storage batteries. Therefore, the cost of total storage system will be decreased significantly, comparing with single battery storage system.

2) System simulation

Before the system simulation, the following assumptions and constraints are made:

System simulation will start under the condition of all storage volumes being equivalent to their design capacity or given volumes.

Hourly production of biogas is the constant. Energy demand for cooking will be met just by biomass power and calculated individually excluding total amount of thermal energy demand. Remain biogas will be used to enhance output of solar thermal power. Wind output will be zero if hourly average wind speed is below 3.5 m/s.

In ith hour, energy output from solar and wind energy can be calculated. comparing those with load demands at start condition, three cases may happen.

Case 1, Supply is more than demand.
Case 2, Supply is less than demand.
Case 3, Electrical power unbalances with thermal power.

After ith hour, simulation will go to (i+1) th hour. Thus it can simulate all conditions of energy system to meet the energy demand. In the period of system design, it can be used to correct scales of different energy sources and storage and check worst conditions. The simulation results were published in another paper.[16] Figure 3 shows the flow chat of simulation.

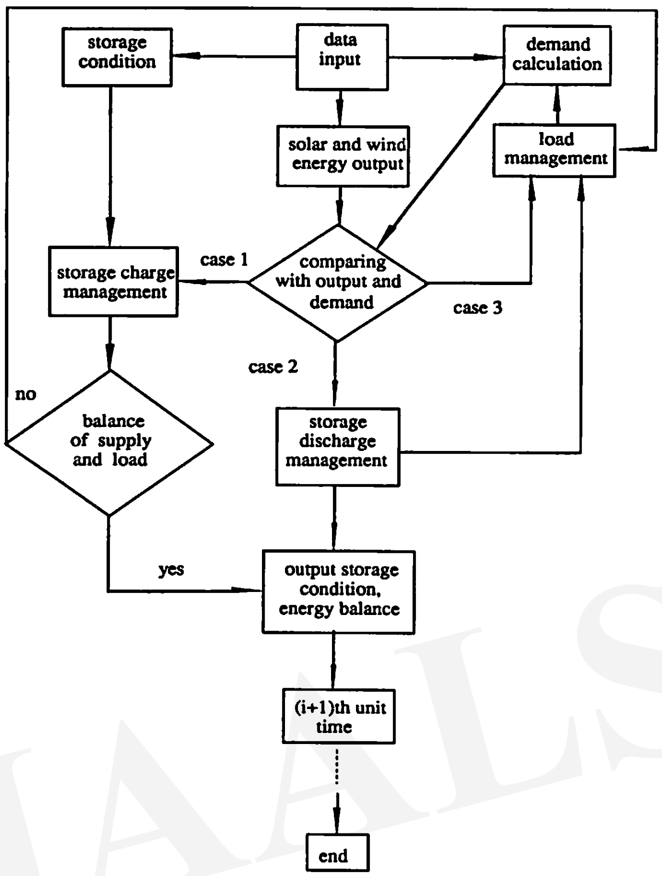

Fig. 3. Fow chat of system simulation

7. Design Example

A new community with no electrical grid connection and a population of 10,000 is chosen as an example for the design and simulation of the integrated renewable energy system presented in this paper. In this example time period is divided into four seasons, spring, summer, fall and winter. Data of design and simulation is also treated in four seasons.[10, 11]

The scales of agriculture and domestics are the follows,

Agriculture

irrigated field area: 100 ha

green house area: 10 ha

cow: 500

swine: 2,000

poultry: 40,000

domestics

residence area: 125,000 m^2

office area: 5,000 m^2

hospital area: 3,000 m^2

merchandize area: 5,000 m^2

others area: 10,000 m^2

1) Natural condition and resources

The depths of underground fresh water and brackish water are 50 m and 20 m respectively. Water balance for agriculture and energy resources potential are shown in Table. 1 and Table 2.

2) Water demand and energy demand

Water demand for agriculture and other purposes is calculated and listed in Table. 3. In this case water demand of agriculture is greater than that for others. The total amount of

Table 1. Irrigation water demand in four seasons.

Seasons	Evaptraspiration (cm)	percolation (cm)	rainfall (cm)	water demand (cm)
spring	31	38.1	10.4	58.7
summer	50.8	38.1	0.8	88.1
fall	24.9	38.1	4.6	58.4
winter	7.6	38.1	17.2	28.5

Table 2. Solar and wind energy potential.

Seasons	Wind speed (m/s)	Solar radiation (kwh/m^2)	Biogas yield (m^3/day)
Spring	5.600	6.589	4,565
Summer	5.900	7.736	4,565
Fall	5.100	6.765	4,565
Winter	4.800	4.816	4,565

fresh water can be calculated.

3) Energy demand

Electricity demand for various purposes can be divided into two parts. One is fixed load and another is variable load. Fixed load means hourly loads and daily sum of hourly load are constants in certain seasons. Variable load means hourly loads and daily sum of hourly load are variable in certain seasons due to using different amount of energy with different ways to realize one target. In this example fixed loads are electricity loads of agriculture, domestics, food processing and storage complex, water treatment plant. Daily and hourly electrical demands of fixed loads in different seasons are shown in Table 4 and Fig. 4.[12,13,14] Variable loads are electricity demands of water desalination and water resources. It will be arranged by load management program according to the amount of daily water demand which is fixed in certain seasons by reasonable distribution of fresh water output from MSF plant, RO plant and UW (underground fresh water).

For thermal demand, in this example, assumes that:

(1) Thermal demand for daily cooking is certain (1 kwh/day per capita) and met by biogas (2,388 m^3/day);

(2) All exhausted heat from solar thermal power will be used for MSF water desalination directly in order to get more high temperature steam.

(3) Other heat needs are low grade ones and will be met by using waste heat from MSF plant and stored heat from solar pond which are assumed greater than the demand.

For scale decision, economical analysis will be involved to find solutions. firstly, annual balance should be satisfied, then consider cost and seasonal balance to make the best solution.

Scales of Renewable energy sources are shown below:

	solar thermal	wind power	PV power	Total
area (m^2)	41,600	42,200	0.0	
rated power (kw)	6,000	2,500	0.0	8,500
yearly output (10^4 kwh)	1,400	1,070	0.0	2,470

The cost of PV is relative high and not selected unless its cost is less than 10 cent/kwh. Annual output of biogas for electricity is 1.58×10^6 kwh. daily output in different seasons is shown in Table 5 and Fig. 5.

8. Conclusion

From Table 4 we can know that domestic loads is the major one among the fixed loads in every season and loads reach at top volume in summer, in other words largest amount of energy will be needed; Table 5 shows that the energy output of solar energy is the major one followed by wind and bio-mass energy respectively in every season and total energy output will raise up to the maximum due to the natural condition in desert in summer. this indicates that supply sources coincide with demand ones as it was mentioned previously.

In the design, the advantages of every renew-

Table 3. Water demand and supply.

Seasons	Water demand of agriculture (m^3/day)		Water demand of others (m^3/day)		Total amount (m^3/day)		Fresh water supply (m^3/day)		Treated water supply (m^3/day)
	1	+	2	=	3	=	4	+	5
Spring	6,610.000		4,500.000		11,110.000		6,835.000		4,275.000
Summer	9,810.000		6,900.000		16,710.000		10,155.000		6555.000
Fall	6,600.000		4,570.000		11,170.000		6,829.000		4,341.500
Winter	3,460.000		2,100.000		5,560.000		3,565.000		1,995.000

Table 4. Seasonal fixed loads.

Seasons	Load of agri. (kwh/day)	Load of domestics (kwh/day)	Load of food proc. (kwh/day)	Load of water treat. (kwh/day)	Total of fixed load (kwh/day)
Spring	6,689.680	28,125.000	3,568.400	4,950.000	43,333.080
Summer	14,844.680	31,000.000	4,005.400	7,590.000	57,440.080
Fall	6,683.680	29,352.000	3,681.300	5,027.000	44,743.980
Winter	3,246.680	28,462.000	3,424.400	2,310.000	37,443.080

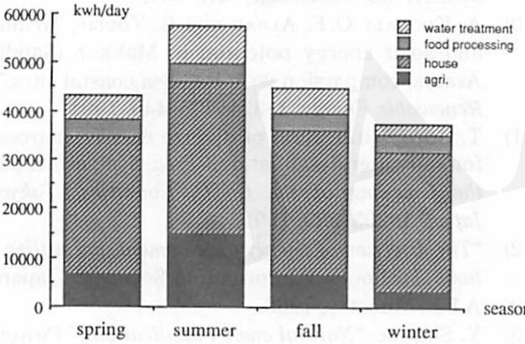

Fig. 4. Daily fixed loads in four seasons.

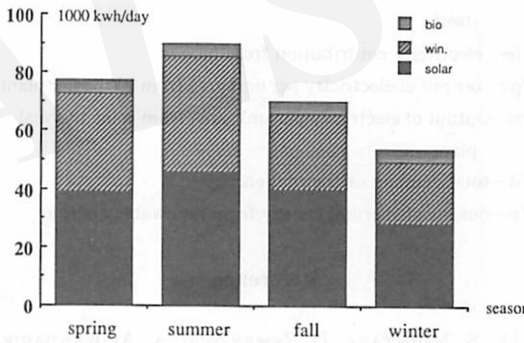

Fig. 5. Daily energy out in four seasons.

Table 5. Daily energy output.

Seasons	Solar output (kwh/day)	Wind output (kwh/day)	Biogas output (kwh/day)	Total output (kwh/day)
Spring	39,104.000	33,760.000	4,329.200	77,193.200
Summer	45,760.000	39,668.000	4,329.200	89.757.200
Fall	39,936.000	25,742.000	4,329.200	70,007.200
Winter	28,288.000	21,100.000	4,329.200	53,717.200

able energy and techniques of using renewables have been enhanced. Load management, biogas and fresh water storage make contributions to operate energy supply system more effectively. All of these make the renewable energy system for oasis feasible.

The IRES for oasis has two functions. One is provide sufficient electricity and heat to meet the energy demand in oasis. The second is that it joins the better ecological circulation of oasis and plays as an active role. It makes possible to create an autonomous and garden-like oasis in which food and daily commodities can be obtained. IRES is also applicable to isolated areas.

Nomenclature

Aps—area of solar pond
Apv—area of solar cells of PV plant
Ast—area of collectors of solar plant
Aw—swept area of wind turbine
Ea—The demand of electricity for agriculture
Ec—The demand of electricity for domestics
Ed—total demand of electricity
Efix—The demand of electricity for fixed loads
Eid1—The demand of electricity for MSF plant
Eid2—The demand of electricity for RO plant
Eif—The demand of electricity for food processing
Eit—The demand of electricity for water treatment
Ep—output of electricity from renewable energy
Evar—The demand of electricity for variable loads
Hbh—heat contribution from biogas
Hsp—output of thermal energy per unit area from solar pond
Hst—output of thermal energy per unit area from solar thermal plant
Kep—coefficient of electricity demand for energy system itself
Pbe—electricity contribution from biogas
Ppv—output of electricity per unit area from PV power plant
Pst—output of electricity per unit area from solar thermal plant
Td—total demand of thermal energy
Tp—output of thermal energy from renewable energy

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Challenge for Desert Rehabilitation through Sustained Mangrove Management

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1. Introduction

Extensive land areas of the earth have been desertified in various ways, including salt damage to soil and destructive human activities. All living things from microorganisms to animals and plants play their respective roles in the physical cycles of the natural ecosystem to establish a suitable natural environment for the area. If part of the biological chain is negatively affected by an external factor the natural ecosystem will in time be destroyed.

It is possible to steadily restore the damaged ecosystem to its original condition if the functions of the elements of the ecosystem are well understood. Much of the forests which were once lush have been damaged by air pollution and acid rain. In recent years, both advanced and developing countries acknowledging the risks, held the United Nations Environment and Development Conference, the "Earth Summit", in Brazil in 1992. Thousands from government and non-government organizations, as well as many private individuals attended.

Except for salt-resistant plants (including halophytes or halophilic plants) or drought-resistant plants, crop plants are probably unable to convert salt-damaged areas or deserts into agriculturally productive areas. In this report, we shall explore ways of rehabilitating the natural ecosystems of arid, tropical and subtropical areas with the focus on mangrove species as typical halophytes.

1) Expected roles of salt resistant plants

The world output of grain has been recorded at around 1.8 billion tons a year since the second half of 1980. This is attributed in part to salt damage to the soil. It is assumed that salt-resistant plants (crops) would facilitate the recovery of productivity of damaged farmland in the following way:

$$1.8 \text{ billion tons/year} \times 2.5/14.8 \times 1/4 = 0.8 \text{ billion tons/year}$$

An increase of about 0.8 billion tons a year is expected. It is also expected that new agriculture technology could be created in India and Africa both facing a serious food shortage due to increased population. Salt-resistant plants could provide the poor with a means of producing agricultural food products.[1]

2) Need for Salt-resistant Mangrove Forest

(a) Resources directly used by inhabitants

The disappearances of mangrove forests in the third world will exert a direct effect on the local inhabitants in need of fuel, building materials and livestock feed in the third world. In Myanmar, 60% of fuel consumption in the capital comes from charcoal from mangrove trees (600,000 tons consumed annually). The trees have many other applications as shown in Table 1.[2,3]

Judging from the use of their products, man-

Table 1. Utilization of mangrove plants.

Timber:	Housing material, Furnitures, Ship-build material, Sleeper paper pulp, Tip Boad, Reyon etc.
Fuel:	Fire wood, Charcoal, Fuel for smoke
Feed:	Feed for camel and goat
Food:	Starch, Vegetable, Fruits
Beverage:	Alcohol, Tea, Juice
Spice:	Vinegar, Sugar
Medicinal:	Hemastatic medicine, Binding medicine, Eye medicine, Fish catch poison
Tannin:	Dye chemicals

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grove forests are probably a source of supplying essential products to everyday life. Creating a new ecosystem of mangrove forests or rehabilitating former mangrove forests will contribute to a better and more stable life to the residents as well as contribution to the recovery of the natural ecosystem.

(b) Mangrove forests stop desertification by seawater action

Intertidal mangrove forests are important for raising prawns, crabs, shellfish and fingerlings and to provide a treasure of marine resources. This is due to the mangrove forests food chain whereby leaves and twigs decay into feed for plankton, which are in turn eaten by fish. In terms of the living environment of fish, mangrove forests stabilize water temperature and provide a shelter to prawn and for fingerlings. In tropical areas, sunlight is strong, and without shade, the shallow sea water would be too warm to support fish. Japanese fishermen have traditionally understood this forest-fish relationship. They have known since the Edo period that "if trees are planted, fish will gather there, and if trees are cut, they will disappear". Therefore, they were not only prohibited from felling forests but were encouraged to plant trees along the coast to increase the catch of fish. These trees have been protected by fishermen named "forests with fish", "forests with nets", "fish gathering forests" or "forests shading small fishes". In 1937, the Bureaus of Fisheries and Mountain Forests in the Ministry of Agriculture and Forestry of Japan conducted a survey of forests by interviewing the people concerned in fisheries about the "effectiveness of forests with fishes". According to the report, these forests contributed to the abundance of marine products by creating a habitat for water microorganisms, basic in the food chain of fish.

Erimo Point in Hokkaido of Japan was once covered with abundant forests. As the area was exploited, inhabitants increased and forests were increasingly felled for fuel. As a result, virgin forests were rapidly devastated and desertified. Strong winds eroded the beach sand and changed the environment of the sea. Migratory fish decreased, seaweed decayed and people could not harvest them. In 1953, afforestation was launched and 70% of the area, or 131 ha, was successfully afforested. Herbs were first planted to take root and then trees were planted. Unfavorable conditions such as frozen topsoil and strong winds were successfully overcome. In times, catches have increased by 29 times from 72 tons prior to planting to 2,100 tons currently.

Mangroves are the most important forests to raise fish in tropical and subtropical areas. If they are destroyed, not only will fish disppear, but coral reefs and the seaweed ecosystem which surround them will be adversely affected and destroyed. If the roots of mangrove trees protecting the coast are lost, earth and sand eroded by waves and currents will build up around coral reefs and weeds and finally kill them. MYERS reported that the primary productivity of mangrove forests was very high compared with other sea areas as shown in Table 2.[4] It is estimated that catches from the tropical coast account for 25% of the world catch.

(c) Conservation of the coastal environment

A strong typhoon recently struck Leyte Island in the Philippines and completely flooded river-mouth towns, where thousands of people died or are still missing. In Bangladesh cyclones regularly visit river-mouth delta areas where huge human and economic losses are reported. If mangrove forests are sound, they will serve as natural breakwater to reduce the force of strong waves and prevent sea water from flowing into and damaging residential areas and paddy fields.

Table 2. Ratio of primary productivity of oceans and esturies areas.

Area name	Ratio of area	Ratio of primary productivity
Oceans	90	1
Continental shelf	9	3
Current water from ground	0.15	4
Saline swamp	0.03	5
A small bay	0.52	14
Coral reefs and sea weeds	0.24	16
Mangrove forests	0.06	21

3) Rehabilitation of mangrove forests

The rehabilitation of mangrove forests has just begun to be taken up as a subject of discussion. This is because damage and suffering attributable to the loss of mangrove forests have created political and economic problems at national levels. Measure for their rehabilitation have seldom been taken, and only a few cases can be now reported.

(a) Why has their rehabilitation been delayed?

(i) The importance of mangrove forests is not well understood.

(ii) There are technical problems in planting trees: although some countries promote mangrove forestation, their techniques are immature and not systematized.

(iii) There are also financial problems: mangrove forestation requires funds, and many countries in need are developing countries.

(iv) Methods of assistance and technical cooperation create problems.

If these problems are understood and resolved, mangrove forests would be gradually rehabilitated.

(b) Actual Situation of Forestation

In Southeast Asia, mangrove trees are found in small stands around villages. This is the result of efforts made by inhabitants to afforest marketable areas for their livelihood.

The actual situation of forestation at the national level are as follow: Matan in Malaysia was afforested the earliest, and *Rhizophora mucronata* and *R. apiculata* trees have reached a height of 20 m. They are cut by rotation of 15 to 20 years to produce building materials, charcoal and firewood. In Thailand, Mangrove Units were set up throughout the country by the Royal Forest Department for conservation and forestation. However, it is said that they have not yet achieved satisfactory results. Bangladesh, which suffers cyclones every year, twice promoted forestation with support from international organizations and the World Bank (from 1980 to 1985, and 1985 to 1990) and achieved largescale forestation covering an area of 800 km^2. In this case, the sypply of fuel to inhabitants was a major objective along with the conservation of ecosystems. The FAO (Food and Agriculture Organization of the United Nations) has also started promoting forestation projects in Bangladesh and Vietnam. In 1990, the UNDP (United Nations Development Programme) launched a mangrove rehabilitation project in Myanmar jointly with the FAO.

Thus, the rehabilitation of mangrove forests has started despite a small beginning. If this trend is expanded into a large movement, the recovery of greenery will begin with coastal areas.

4) Rehabilitation of mangrove

Kogo *et al.* have planted mangrove trees on Mubaras Island in Abu Dhabi since 1980. It is reported that crude oil which leaked at the time of the Gulf War seriously affected most of the mangrove species raised in the study plot. Nevertheless, they obtained valuable data. As mangrove grew, crabs appeared first and settled. At high tide, shoals of small fish appeared as well as large fish. Several species of shellfish also began to live around mangroves, and bivalves like short-necked clams were seen. Sea birds such as Temminck's cormorants and sea gulls came to Mubaras Island in the winter along with marine animals and plants. Just after an ecosystem began to be established in this way, crude oil unfortunately caused mangroves to wither.[5]

(a) Expenses of mangrove Forestation

A case of forestation under way in Thailand will be introduced. The species used were *Rhizophora mucronata* and *R. apiculata* which have a high economic value. These species have viviparous seeds, they do not require the production of seedlings, and are economical as seeds can be directly sowed in the intertidal zone. Seeds collected by habitants are purchased at 75 yen per 100 for *R. mucronata*, 85 yen per 100 for *R. apiculata* and 50 yen per 100 for *Ceriops tagal*. Three years planting and management costs 38,000 yen per ha. This total is broken down into 30,000 yen in the first year, 5,000 yen in the second year and 3,000 yen in the third year. In Malaysia, these operations are entrusted to contractors. The cost of a four-year management contract is about

50,000 yen per ha. The cost of the Forest Department doing it directly ranges from about 35,000 yen to 100,000 yen.

In developing countries, forestation costs are mostly for labor, and the cost of the plants themselves is extremely low. It is reported that forestation costs 1.75 million yen per ha in Florida, fifty times higher than in Thailand, and it costs 4.06 million yen per ha in Brisbane, one hundred times higher.

(b) Model area for mangrove forestation

Many studies show that about 3,000 years ago desertified Middle East gulf countries were covered with rich vegetation. According to the study by KOGO *et al.*, mangrove forestation has proven feasible in a few areas, where planted trees have grown well, and life including fish have actually returned.

It seems to be an urgent task from the standpoint of global conservation (addressing the issues of global warming and CO_2 fixation) that greening should be carried out promptly in the gulf countries before other areas. If a green breakwater is built along the gulf, various species will begin to live around mangrove trees and create a biological chain similar, though with different species, to that of mangrove forests in Southeast Asia. Plants resistant to salt (from weeds to crops) will also take root area developing into grassland on the land side of mangrove forests. A vegetational environment adjoining the grassland will be gradually established inland to facilitate the growth of not only halophytes but also general crops and plants which are not resistant to salt.

5) The creation of mangrove forests on the coast

The establishment of mangrove forests will bring about various benefical effects. The direct benefits will be:

(a) Timber use: including firewood, building materials and pulpwood.
(b) Better ecosystem: catches of fishes, prawns and crabs will increase; beekeeping and feeding birds and mammals will be possible.
(c) Tide control effect: building and land under cultivation will be protected against cyclones and typhoons.
(d) Prospective applications: mangrove forests could be used as resources for tourism, education and recreation; mangrove parks could be constructed (places for recreation and relaxation currently in Florida, Australia, Hong Kong and Singapore).
(e) Medicinal use: many mangrove species are locally used for medicinal purposes.
(f) Protection and production of farmland against salt damage.
(g) CO_2 fixation, oxygen production and transpiration.

Moreover, the livelihood of local people will be supported, and agriculture will be possible even in formerly sterile deserts without large-scale facilities. If plants are distributed, they will raise air humidity and prevent the air from drying. They will also transpire from their leaves, and vapor will be cooled to produce precipitation.

6) What is a halophilic mangrove?

(a) Forests in the Sea

"Mangrove" is a generic term for plant communities distributed in the intertidal zone affected by sea water on the coast or in the mouth of a river in tropical and subtropical areas. They are salt-resistant plants of great interest to researchers and people interested in environmental problems. Historically, they caught the attention of people because of their uniqueness. In recent years, they have begun to be studied in terms of why these plants form a large forest zone in sea water. Mangrove species are also the subject of research for genic resources of salt-resistant or halophilic plants. Mangrove forests are also important areas where fingerlings are produced and the local people make a living. In addition, they serve as a breakwater and reduce damage by typhoons and other natural disasters.

The term "mangrove" is an English word, but is actually a combination of "mangue", a Portuguese word meaning "trees which grow well in boggy areas on the coast", and "grove", an English word meaning "a wood or a stand of trees".

(b) Mangrove forest issues

The global distribution of mangrove forests has been reported in detail by H. BARTH.[6] As the area of such forests has been rapidly decreasing, there are fears that mangrove forests will disappear from the earth. Table 3 shows data on the worldwide distribution of tropical rain forests and mangrove forests in 1980. The total area of tropical rainforests was about 1.2 billion ha, while that of mangrove forests was about 15.5 million ha. On a continental basis, mangrove forests made 5.78 million ha in tropical America, 3.4 million ha in tropical Africa and the largest area, about 6.3 million ha, in tropical Asia.[7)]

The economic development of Southeast Asia has been remarkable. Densely populated coastal areas were easy to develop and were

Table 3. An area of tropical rain forests and mangrove forests of world.

Area name	Forest area (unit: 1,000 ha)	
	Tropical rain forests	Mangrove forests
Tropical America (23 countries)	678,656	5,781 (37.4%)
Tropical Africa (37 countries)	216,634	3,402 (22.0%)
Tropical Asia (16 countries)	305,510	6,279 (40.6%)
Total (76 countries)	1,200,799	15,462 (100%)

Table 4. Strict mangrove species.

Family name	Species name	
Avicenniaceae	*Avicennia marina**	*Avicennia germinans*
	Avicennia alba	*Avicennia africana*
	Avicennia lanata	*Avicennia bicolor*
	Avicennia offcinalis	*Avicennia balanophora*
	Avicennia eucalyptifolia	*Avicennia shaueriana*
Combretaceae	*Laguncularia racemosa*	
	Lumnitzera littorea	*Lumnitzera racemosa**
	Terminaria catapa	*Conocarpus erecta*
Meliaceae	*Xylocarpus granatum*	*Xylocarpus moluccensis*
	Xylocarpus mekongensis	
Myrisinaceae	*Aegiceras coruniculatum*	*Aegiceras foridum*
	Ardisia elliptica	
	Myrsine umbellulata	
Plubaginaceae	*Aegialitis annulata*	*Aegialitis rotundifolia*
Rhizophoraceae	*Bruguiera gymnorrhiza**	*Bruguiera parviflora*
	Bruguiera sexangula	*Bruguiera cylindrica*
	Bruguiera exaristata	*Bruguiera hainessi*
	Rhizophora apiculata	*Rhizophora selala*
	Rhizophora mucronata	*Rhizophora mangle*
	*Rhizophora stylosa**	*Rhizophora harrisonii*
	Rhizophora samoensis	*Rhizophora racemosa*
	Rhizophora lamarckii	
	Ceriops tagal	*Ceriops decandra*
	*Kandelia candel**	
Rubiaceae	*Scyhiphora hydrophyllacea*	
	Rustia occidentalis	
Sonneratiaceae	*Sonneratia caseolaris*	*Sonneratia alba**
	Sonneratia apetala	*Sonneratia griffithii*
	Sonneratia obata	

*: Six species grow in Okinawa, Japan.

Table 5. Mangrove plants as medicinal herbs.

Species name	Part of plant	Efficacy
Acanthus ebracteatus	Leaves	Leumatis
A. ilicifolius	Leaves	Leumatis
Avicennia africana	Seeds, Barks	Ulcer, Tumor
Av. alba	Seeds, Barks	Parasitism infection
Av. germinans	Seeds, Resin	Paratisism infection
Bruguiera gymnorrhiza	Fruits	Medicine for eye
B. sexangula	Fruits	Medicine for eye
Cerbera manghas	Fruits	Leumatis
Ceriops tagal	Barks	Hemostatis drug
Excoecaria agallocha	Barks	Binding medicine
Heriteria littolaris	Seeds	Binding medicine
Lumnitzera spp.	Leaves	Ulcer
Rhizophora mangal	Barks	Hemostatic drug
R. mucronata	Barks	Hemostatic drug
Sonneratia alba	Fruits	Hemostatic drug
S. ovata	Fruits	Hemostatic drug
Xylocarpus spp.	Barks	Cholera

chosen first under national development projects and the pressure of the increasing population. As a result, mangrove forests were felled to construct roads, factories and houses. In addition to timber production, the logged-over areas have been used to cultivate crops, produce marine products of to tin mining (on the coast of Malay Peninsula). The timber can be used for firewood, building materials or shipping materials and is locally used or exported. Mangrove charcoal is a highcalorie fuel providing the most important source of energy to the local people. Consequently, mangrove forests are disappearing.

The total area of mangrove forests in Thailand had halved from the 368,000 ha in 1961 to 176,000 ha in 1979. This trend has not weakened in the 1980's. Mangrove forests have actually disappeared on the coast of the Gulf of Thailand, decreased by 90% on the east coast of the peninsula in about two decades. Many of them were converted into prawn farms, now abandoned as their production efficiency is reduced by diseases. In this situation, it will take time and a relentless effort to restore mangrove forests to their original condition.[8]

(c) Distribution and Species of Mangrove Forests

Mangroves are randomly distributed within the tropics. Japan is the northern limit of their distribution, and *Kandelia candel*, the most resistant to cold, is found in Kiire-cho in Kagoshima Prefecture. Six species of natural mangrove occupy an area of about 400 ha in the southwestern island in Okinawa. In countries where mangroves are found, they have been used as medicinal herbs (Table 5).

There are 116 listed mangrove species, very few for a tropical rain forest, attributed to their living environment. Mangrove forests extend from coast to inland so that plants in the coastal zone are not easily distinguishable from those in the inland zone. Therefore researchers have different opinions on whether a plant should be included in the mangrove category. Constituent species of mangroves are largely divided into three groups, namely strict, sub and minor mangrove species. Strict mangrove species (pure mangrove species) are the mainstay of mangrove forests, with their own characteristic shape and physiological features. They are distributed in the front of mangrove forests derectly affected by sea water or along tidal rivers. Table 4 shows eight families and 50 species of strict mangrobe species. They include all strict mangrove species throughout the world.[1]

Southeast Asia is blessed with a variety of species and provide a good environment for their growth. It is said that mangrove plants originated in Southeast Asia, around the Malay Peninsula. They are distributed along the long coastline of the Indochinese Peninsula, on the Peninsula of Thailand and in Malaysia, the Philippines, Indonesia, New Guinea and Pacific Islands, Australia and New Zealand. They are also found at the mouth of the Ganges (Sundarbans) and distributed from the coast of the Indian subcontinent to the east of Africa.

Mangrove distributed in the Indian and Pacific Oceans, consist of a certain group of species and are called Indian and Pacific or oriental mangroves. Mangroves distributed in the west coast of Africa and north and south america are called Atlantic or occidental mangroves. CHAPMAN classified mangrove plants into a total of 90 species, of which 63 species are found in the Indian and Pacific region, and 17 species in the Atlantic region. Rhizophoraceae (*Rhizophora* spp.) is mainly distributed in the former, while Avicenniaceae (*Avicennia* spp.) is mainly distributed in the latter. Many researchers are currently interested in how major species of mangrove forests in these regions developed and are examining their differences.

(d) Features of mangroves

The large environmental difference between mangrove habitat and that of land plants is that the former are distributed in areas subject to tidal or regular flows of sea water. The distribution of many species of plants in sea or brackish water shows a unique zonation (from a distance, they look to be distributed in communities of species from riverside to inland). The zonation indicates that every species can grow only in its particular environment.

MACNAE points out three conditions of zonation: (1) frequency of immersion of the mangrove area due to tidal ebb and flow, (2) mangrove's resistance to salt content of sea water, and (3) erosion of internal and peripheral waterways of the mangrove area and the mangrove coast.[9] CHAPMAN notes that ecological factors in the development of mangroves include: (1) ebb and flow, (2) salt content, (3) soil structure, (4) level of underground water and drainage, (5) airing, (6) chemical properties of soil except sodium chloride, (7) climate, and (8) biologiocal conditions. Mangrove forests, free of human activity, in Southeast Asia or the South Pacific region are indeed magnificent.[2]

(i) Roots of mangrove plants

Mangrove plants have respiratory roots of various shapes with which they breathe in mud which is regularly immersed in sea water. Some plants under *Rhizophora stylosa* distributed among the coast grow long suspensory roots from the stem to the ground, while others grow prop aerial roots, like octopus tentacles form the stem into the ground at the highest tide. *Bruguiera gymnorrhiza* grows geniculate roots which look like the bent knee of a human being when they are exposed at low tide. *Sonneratia alba* and *Avicennia marina* grow straight roots perpendicularly from lateral roots in the ground toward the surface. *Xylocarpus granatum* grows plate roots.

The mud in which mangroves grow has hardly any detectable oxygen at a depth of about 15 cm, and the measured redox potential shows a state of reduction. Some mangrove species which grow in brackish water keep their internal salt concentration low by discharging the once-absorbed salt through the cation of ATPase existing in the cell membrane of the root as well as the shape of the root. It is conventionally understood that oxygen is supplied to roots in the mud through respiratory roots in spite of such severe conditions. Since chlorophyll was found in the slightly peeled outer layer of a straight root or prop aerial root, the amount of oxygen replacement was measured in aerial root of *Sonneratia alba*, *Avicennia marina*, *Rhizophora stylosa* and *Bruguiera gymnorrhiza* on Iriomote Island, Okinawa. The relationship between the level of tide water and the oxygen supply function of these aerial roots were examined in the light of the same function of aerial roots distinctive of each species. Aerial roots of *Sonneratia alba* showed the highest speed of photosynthesis and therefore the highest speed of generating oxygen of the four species.

The effect of solar radiation and tide level on the speed of transpiration were examined by measuring daily changes in the speed of transpiration of *Sonneratia alba*. With regards to oxygen replacement by aerial roots of the four species, the speed of generating oxygen increased in this order: *Rhizophora stylosa, Avicennia marina* and *Sonneratia alba*. Aerial roots of *Bruguiera gymnorrhiza* are not capable of generating oxygen.[10,11] The speed of transpiration of *Sonneratia alba* rose as solar radiation rose. It was 3–4 $g/dm^2/h$ at a radiation of 700 w/m^2 (about 1 $cal/cm^2/min.$), almost the same as the figure for herbaceous plants such as cucumber and tomato. In response to such a high speed of transpiration, roots existing in brackish water at the atmospheric pressure of 20 to 30 need much energy to supply water. This energy is presumably generated by roots breathing. It is suggested that the oxygengenerating function of aerial roots through photosynthesis is important for supplying oxygen required in the process.

(ii) Leaves of mangrove plants

Various ions which have passed through the cell membrane of the root will be carried through transpiration from leaves to the upper part above the ground and used for growth. However, excessively absorbed Na and Cl ions will be gradually accumulated in leaves or discharged as salt (NaCl) from salt glands distributed over the surface of the leaf. *Avicennia marina*, which has salt glands over the surface of the leaf, was cultivated in cultivation liquid solution with salt concentration of 0 to 3.0%. As a result, it was found that a certain quantity of salt was discharged from the salt glands as the salt concentration of the cultivation liquid increased. The analysis of the discharged salt showed that it was almost entirely composed of NaCl. Nutritious salts required for growth were hardly discharged.[12]

On the other hand, mangrove species which have no salt glands adjust osmotic pressure to avoid physiological disorders by diluting the cell sap while enlarging the vacoule or by neutralizing excessive cations with organic acids in response to various ions excessively absorbed or taken into leaves.

(iii) Seeds of mangrove plants

Since they grow in an environment under the influence of ebb and flow, mangroves must have seeds more adaptable to the environment than land plants. One feature of some mangrove plants is viviparous seeds, as seen in Rhizophoraceae. Viviparous seeds are formed in fruits after flowering and pollination and develop roots called rhizophores prior to falling. When they have well matured, they fall onto the ground and are scattered around the tree or to remote areas, where they quickly take root to survive (also called disseminule). The size of these seeds range widely from about 10 cm to about 1 m (*Rhizophora mucronata*).[13]

(e) Mangrove stabilize the natural environment

Varying with species, the existing biomass of mature mangrove forests in a good environment is 140 tons/ha in stems (Thailand and Florida), 160 tons/ha to 280 tons/ha (Panama) and 300 tons/ha (Thailand) in the part above the ground including branches and leaves, and from 170 ton/ha (Iriomot Island) to 430 tons/ha (Thailand) in roots. The leaf area indices (LAI) range from 3.7 to 8.9 tons/ha. These figures are comparable to the biomass of tropical rain forests above the ground, which range from 330 to 660 tons/ha (Thailand and Malaysia).

From the standpoint of global conservation, the first function of mangrove communities is to fix CO_2. The abovementioned figures indicate biomass in a good environment. Carbohydrate exists at a rate of 150 tons per ha on the assumption that the existing mangroves, including roots in an average environment amount to 250 tons/ha, the average water content is 40%. The whole quantity of biomass is composed of carbohydrate, and carbon atoms come from CO_2. Assuming that such carbohydrate is sugar, 220 tons of CO_2 per ha is used to generate it. It is obvious that the amount of CO_2 discharged in the air will never decrease, but continue to increase, as long as fossil fuel is continued to be used in the future. One method for preventing such an increase is to nurture mangrove communities on a large scale using brackish water areas where forestation does not compete with agricultural development.

The second function of mangrove communities is to improve and stabilize the climatic environment around them through active transpiration from leaves having larger apertures than ordinary plants as well as high resistance to salt. It will provide an important means of sustainable forestation of semiarid areas in tropical and subtropical zones where only saline water is available.

The third function is to maintain a variety of natural ecosystems. Mangrove communities in widely fluctuating tidal zones can facilitate the sedimentation of earth and sand from upper reaches and reduce their influx into coral reefs. The bottom mud of the communities also provides a favorable place for various fish, prawns, crabs, and shellfish to spawn and for fingerlings to grow. Small pores made by these small organisms in turn supply oxygen to the roots of mangroves and prevent harmful gas such as hydrogen sulfide from accumulating. Thus, they have a kind of symbiotic relationship to improve the living environment.

(f) Measures to rehabilitate the second tropical mangrove forest

Foresting semiarid areas in tropical and subtropical zones has two main elements. First, to improve the surrounding environment, including techniques for sustainable forestation. Second, to answer the local expectation for the efforts of the effects of such techniques on economic output and environment.

The main purposes of rehabilitation are to plant trees along the coast of desert areas, to fix CO_2 which has been increasing year by year, and to contribute to increasing food production. It should be from an international or global point of view, addressing general problems of the maintenance and conservation of the damaged global environment.

(g) Mangrove plants and global ecosystems

Plants play a major role in cleaning the global environment through photosynthesis whereby they maintain themselves by using and fixing CO_2, the probable cause of global warming. The amount of CO_2 actually absorbed by forests to supply oxygen depends on species, tree age, soil and weather conditions. Thirty tons of timber in one hectare of forest will annually consume 144 tons of CO_2 from the air, and discharge 108 tons of oxygen. Trees themselves will absorb 72 tons of oxygen required to survive and discharge 96 tons of CO_2. It is finally calculated that they will absorb 48 tons of CO_2 and discharge 36 tons of oxygen. Therefore, one hectare of forest will supply oxgen for 120 to 130 people. Mangrove plants, which survive under severe conditions, are not inferior to land plants in photosynthetic capability. If unplanned and unlimited development is carried out, it will exceed the regenerating capability of the ecosystem. The reversibility of the changed ecosystem should be well understood. Natural withering is usually within the regenerating capability of the ecosystem.

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Opportunities and Constraints for Developing New Industrial Crops Adapted to Arid Lands

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1. Introduction

New industrial crops, for manufacture of non-food and non-feed products, are being recognized as a means for solving some of the problems facing agriculture today. Over the past decade, considerable interest has been generated for utilizing new arid-land industrial crops for the production of rubber, resins, coatings, fibers, newsprint, lubricants, pharmaceuticals, and cosmetics.[1, 6–11, 13–16, 17, 18, 20] Development of new industrial crops, which are well adapted to and appropriate for production in arid lands, significantly contributes to the agricultural economy benefiting the producer, processor, consumer, and environment.

Agricultural production in semi-arid and arid regions is heavily dependent upon water availability and cost. Water requirements for most major crops range from 100–200 cm/ha.[11, 15] World-wide agriculture functions on a very narrow germplasm base with less than 0.2% of the estimated 300,000 plant species utilized in organized agriculture.[15] The world's food supply is essentially based upon seven crops, including wheat, rice, maize, barley, soybean, common bean, and potato. All of these and most other major crops of the world are mesophytic, and not well adapted to cultivation in arid lands without significant quantities of supplemental irrigation. In many instances, it is illogical to grow conventional, low-valued crops on lands with limited and increasingly expensive water supplies in competition with stable cropping systems on non-arid lands. Additionally, growth of conventional agricultural crops under stressful arid conditions frequently leads to deterioration of the soil, reduced productivity, and may contribute to desertification.

If agriculture is to continue to function as a viable economic force in arid and semi-arid regions, producers must have alternatives. Development of new crops is a major agent for change and provider of new alternatives.[7, 10, 11, 13, 17, 18] For any new crop to succeed, it must address a real or perceived need, and it must ultimately do so at less cost, or have some economic advantage over an alternative source. We may therefore define a "new crop" as one that is developed or adapted to be grown for production of agricultural or industrial products, which do not compete with or substitute for existing agricultural commodities within a given production area.[16] There is little economic sense in developing a new crop that produces a commodity, which isnot significantly different qualitatively or quantitatively from one already in production. If a new crop does not offer a real alternative, little enthusiasm is likely to be generated in the production, processing, marketing, and consumption sectors, or within industry in general.

The components of most major agricultural crop systems; production, processing, marketing, and consumption, have evolved over a considerable period of time. In most instances, these components have co-evolved to accomodate new research and production developments, marketing opportunities, and constraints. Development of a new crop requires a similar process, but numerous factors make it difficult to bring the new system's components into full harmony and productivity within a reasonable period of time. The creation of a crop that is adapted for culture in an arid environment usually presents additional challenges, opportunities, and constraints. The objective of this paper is to illustrate the process of developing a new arid-adapted crop based upon our current efforts to domesticate and commercialize lesquerella [*Lesquerella fendleri*

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(Gray) Wats.], a potential source of hydroxy fatty acids for industrial products.

2. Factors to Consider in Choosing a Potential New Crop

Certain arid-adapted plants, which produce materials useful as chemical feedstocks, may have a competitive advantage over conventional crops grown under arid conditions since they may produce a higher value product and have high water use efficiency. However, essentially no high-valued industrial crops have as yet been developed and fully commercialized.

The rewards of new crop development are high, but it is not an easy task, and the probability of success for any specific venture is relatively low. Numerous attempts to commercialize a new crop have been speculative and poorly planned, resulting in frustration, failure, and financial losses to farmers and other participants. Two important constituents must be involved in the new crop developmental process: (1) the innovator who conceives and conducts the necessary research to demonstrate effectively the uniqueness and potential, and (2) the private industry decision maker who receives the transfer of technology, and brings the new crop and its products to the marketplace.

To be successful, a realistic assessment of actual or potential markets for the primary product and any generated coproducts must be made. This is best accomplished through the systematic involvement and collaboration of federal, state, and industrial sectors in the conception, planning, funding, execution, and critical review of all phases of the developmental process.[17] A whole array of questions must be addressed to the various sectors of the production, processing, marketing, and consumption system. Important questions relate to the uniqueness of the new product. Is the product well differentiated? Who are the customers for the product? How well will the new product compete on the basis of price or performance? What is the value, and how will the value be recognized and captured? [23]

Other questions relate to the area of adaptation of the new crop and its feasibility for adoption at the farm level. Some questions that must be addressed are: the availablity of suitable land and water resources; availability of other inputs such as seeds, fertilizers, and labor; productivity of competing crops, and compatibility with existing farming systems; needs for specialized equipment for production and harvesting; susceptibility to pests, weeds, and environmental hazards; availability of marketing information, and production credit; existence of governmental services and regulations that would affect production; and the management skills needed for successful production.[14,17]

Equally important questions relate to the marketing and processing components of the system. Some of these deal with the adequacy of supply, transportation, and storage facilities for the agricultural product to be processed; availability of methodology and equipment for processing; adequacy of research on processing and utilization; availability of marketing information; and the existence of governmental services and regulations that would affect the distibution, processing, and marketing of the product.

It is evident that the total process of developing a new industrial crop is highly complex and involves numerous interactions at many levels. A systematic approach to developing new technology and moving it through the commercialization process has been referred to as "Opportunity Analysis".[23] The purpose of the analysis is to provide a framework for asking and answering various production, marketing, manufacturing, technological, and ultimately financial questions. This structured examination of an innovation can and should be applied to the development of a new industrial crop. In most instances the Opportunity Analysis cannot or need not have been completed in its entirety to make informed decisions regarding the potential of a new industrial crop. It is not uncommon that critical information about one or more components of the proposed new product may be incomplete or missing. In these circumstances, the analysis can be effectively used to focus research anddevelopment on critical questions so that answers can be obtained in a timely manner.[23]

1) Special requirements for an arid-lands adapted crop

Plant productivity in arid areas is closely related to water usage, and water is usually the primary economic input for production. Therefore, an economically viable new crop must use less water, and use it more efficiently than conventional crops. However, development of a highly productive new crop that uses less water is easier said than done.[18] It is mistakenly believed that desert plants utilize water more efficiently than non-desert plants or conventional crops. Many desert plants are actually less efficient, since many of their adaptive mechanisms that conserve water also concurrently reduce photosynthesis and dry matter production.[8, 11, 15, 18] However, most desert plants use water more efficiently when water is limited, and can survive long periods of water stress. Desert plants will usually not grow or produce much biomass during extended periods of water stress, but they have the capacity to survive and reproduce under conditions causing death and complete crop failure of most mesophytic plants.

A good example of this is the guayule plant (*Parthenium argentatum* Gray), which is currently undergoing development as a new industrial crop for the production of natural rubber and resin. Guayule is a true xerophytic plant that is native to the Chihuahuan desert region on north-central Mexico and southwest Texas. Annual rainfall in its natural habitat varies from 230–400 mm, and plants have been known to survive for considerable periods of time without rainfall. Extensive studies have been conducted by USWCL in Arizona to determine the relationship of guayule water use and production.[12, 20] Biomass, rubber, and resin yields of guayule grown in an arid environment are greatly enhanced by irrigation. Yield increases were closely related to the amounts of water added. It has been concluded that optimum production will not be achieved under most cultural conditions without using moderate to heavy applications of irrigation water, since rubber and resin yields are so highly dependent upon yield of biomass.

To obtain the greatest efficiency of production in an arid environment, one needs to select species that yield products with high value per unit area of land, and have little dependence upon the extent of biomass production. Poor candidates as new crops for arid environments are hay, grain, most oilseeds, sugar, pulp, and fiber crops, which are consumed in relatively large quantities and have relatively low value. In contrast, plants producing significant yields of relatively high-valued industrial feedstocks and products such as oils with unique fatty acids, essential oils, rubber, resins, gums, waxes, pharmaceuticals, cosmetic ingredients, and biologically active materials are prime new crop candidates for arid lands.[8, 11, 15, 18]

A third criteria, which is little appreciated and poorly understood, is that any new industrial crop developed for arid lands must be poorly adapted for production in more humid areas.[11] The reason for this is that production costs in irrigated, arid-land agriculture are usually significantly higher than that of rain-fed agriculture. Even though yields may be higher, the unit costs of producing crops in arid lands are almost always higher than in rain-fed areas. Therefore, if a desired, new industrial feedstock is to be successfully grown in arid lands, it should not receive significant competition from non-arid production areas.

3. Factors Involved in the Selection of Lesquerella

Numerous factors were considered in selecting lesquerella as the candidate crop. One of our primary concerns was to identify species that could be grown under arid conditions, have high economic value, and bring improved monetary returns to farmers with lower water usage. Another criteria was to develop a crop for domestic production that could be utilized readily by industry. Without industry's active participation at the early stages of domestication, success cannot be assured.

The United States and most industrialized countries are totally dependent upon imported castor oil as a source of hydroxy fatty acids. Hydroxylated fatty acids are utilized in the manufacture of high performance lubricants and additives, corrosion inhibitors, coatings, plastics, nylons, resins, waxes, pharmaceuticals, and cosmetics. It was envisioned that a new domestic source of lesquerella oil could complement the use, and partially replace castor oil in some current industrial applications. The longer carbon chain length (C_{20} for lesquerolic acid vs. C_{18} for ricinoleic acid from castor oil) should provide opportunity for developing new and unique applications and products. Much of the reasoning that entered into this decision is summarized in a recently published bulletin entitled "Lesquerella as a Source of Hydroxy Fatty Acids for Industrial Products".[14] Other publications detail and document the current status of our efforts to fully commercialize lesquerella.[4,5,6,7]

1) Germplasm collection, evaluation, and enhancement

Many of the species of the genus *Lesquerella* are native to the arid and semi-arid areas of southwestern United States. Presumably, these species should have lower water requirements, and better arid-land adaptation than the castor bean. *L. fendleri* was selected as the most promising candidate species for domestication after evaluating the available germplasm in experimental field plots in central Arizona.[15,16,18] This species has a wide range of genetic diversity and adaptation in arid and semi-arid areas from southeastern Arizona to Texas and Oklahoma. Many of the plants observed within the population had good agronomic characteristics such as high seed yield, erect plant growth, lack of seed dormancy, and reasonable contents of oil (±25%) and lesquerolic acid (±55%) in the seeds. However, certain attributes of this species are less desirable, and can create obstacles to its full commercialization. The small seed size of this species, ±0.6 g/1,000 seeds, creates problems in the establishment of adequate plant stands. Seedling plant growth is slow, and the plants are poor competitors with weeds.

Research was initiated in 1984 at the USDA-ARS U.S. Water Conservation Laboratory (USWCL), Phoenix, Arizona to evaluate germplasm and determine the feasibility of domesticating lesquerella. Our initial germplasm pool consisted of 24 accessions of *L. fendleri*, from which we made selections and developed breeding populations. These populations were used for further selection and for agronomic research. Results over the 1984 to 1991 period were recently summarized and provide a bench mark upon which future progress in varietal and population development can be measured.[19]

Higher oil and lesquerolic acid contents and seed yields would greatly enhance the success of commercialization. Fortunately, genetic variability within the genus is broad, and germplasm is available for making improvements in agronomic characteristics and chemical constituents.[8,19,21,22] In 1992, a major germplasm development effort was initiated at the USWCL to select favorable combinations of seed, seed oil, and fatty acid yields. Recurrent selection breeding populations have been developed from the highest yielding selections. The incorporation of molecular genetic techniques into our germplasm development program has been initiated to enhance our progress.

In addition, one of our industrial partners, Mycogen Plant Sciences, San Diego, California, has launched an extensive effort to develop proprietary varieties or populations to supply the projected demands for planting seed stocks. Their approach is to combine applications of biotechnology to conventional plant breeding and genetic methods to accelerate the process. This effort to develop infrastructure for seed improvement, production, and distribution is highly essential to the commercialization effort.

In 1993, we initiated an extensive, multiyear project to thoroughly collect and evaluate germplasm of *Lesquerella* throughout its natural range in the United States. We are also collecting the closely related genus *Physaria*, the seeds of which also produce hydroxy fatty acids. Some *Physaria* species are adapted to high elevations and arid environments, and may contribute valuable genes in the future. Our first year's effort, chiefly in Arizona and New Mexico, resulted in the collection of 92 new accessions, including 49 of *L. fendleri*, and 39 of 10 other species of *Lesquerella*. Four new accessions of two species of *Physaria* were also collected. Six of these species are completely new to our germplasm collection. Several of these new collections have agronomically desirable characteristics, which we will be introducing into our working germplasm pool through breeding and selection.

2) Development of an appropriate crop production system

Concurrent to the initiation of germplasm evaluation and improvement, agronomic research was initiated to develop appropriate cultural and harvesting methods. One of our primary objectives was to utilize, if possible, a crop production system that employed conventional methods and equipment. Use of normally accepted practices should simplify acceptance by farmers, and minimize costs of production. Research was conducted in cooperation with the University of Arizona at the Maricopa Agricultural Center on seeding rates and meth ods, water use and management, weed control, nutrition, and harvesting methods.[4,5,14,21] Cooperative agronomic research has been initiated with university and industry scientists in California, New Mexico, Oregon, Texas, and Virginia. Support for this effort has come from the Department of Defense through the USDA Office of Agricultural Materials.

Significant effort has been expended on determination of water requirements and water management for lesquerella. In general, a seasonal requirement of from 550 to 650 mm of water is needed for optimum production.[4,5,14] This is about the normal amount of water needed to produce a winter wheat crop in central Arizona, and is less than that used by other crops such as alfalfa and cotton produced in this area. Current research is targeted toward determining stress behavior, and response of the crop to water applications during various stages of growth, particularlyover the flowering and seed maturation stages. Such information is needed before definitive irrigation scheduling guidelines can be developed.

In the wild, the species generally grows as a short-lived perennial. However, the plants are normally grown as an annual under our system of culture. We have discovered that if the plants are still living at harvest, it is possible to revive the plant with an application of water and obtain subsequent regrowth. We are exploring the possibility of growing the plant as a perennial under rainfed conditions, with or without a small amount of supplemental irrigation. This could lead to the development of a less expensive production system, which may permit the use of lower valued lands, and savings in water and its related cost.

Research to date indicates that no insurmountable production problems exists, and that conventional farming methods and equipment can be used with minimal modifications. Although this is true, considerable agronomic research is still needed to obtain reliable seed production. Much of the difficulty is attributed to the very small size of the seeds, and the slow, noncompetitive growth habit of the seedling plants. Current research is focused on seed bed establishment, and control of weed competition. A long-term approach has been initiated to remove this constraint through the genetic development of new varieties with larger seed size and improved seedling vigor.

3) Oil extraction and utilization research

The initial chemical screening of the *Lesquerella* germplasm was conducted at the USDA-ARS National Center for Agricultural Utilization Research (NCAUR), Peoria, Illinois in the 1960's. This research identified lesquerolic acid and two other potentially useful hydroxy fatty acids, auricolic and densipolic acids in the seed oil. Research on extraction and utilization of seed oils and meal is currently in progress.[2,3] Cooperative feeding trials to determine the nutritional value of lesquerella seed meal are being conducted on beef cattleat the University of Arizona, Tucson, andon chicks and rats at Kansas State University, Manhattan. Utilization research conducted by industry to develop lubricants and additives is also in progress. Research to develop and utilize cosmetic grade oil from lesquerella by one of our industrial cooperators, International Flora Technologies, Apache Junction, Arizona, is proceeding.[1]

4) Technology transfer and cooperative commercialization

In 1989, only five years after the initiation of our efforts to domesticate lesquerella, we were approached independently by International Flora Technologies, and by Mycogen Plant Sciences in regard to the possibility of commercializing lesquerella. The focus of interest of the two companies was not in conflict, and neither were primarily interested in utilizing lesquerella oil as a substitute for castor oil. Flora Tech, one of the major processors and suppliers of cosmetic grade jojoba oil, was primarily interested in the use of the oil and its derivatives in the cosmetic industry. Mycogen Plant Sciences (formerly Agrigenetics Company, a subsidiary of the Lubrizol Corporation) was interested in the oil's potential for specialty lubricants and oil additives. Both potential applications were for the manufacture of products with significantly higher value than those derived from castor oil.

From these initial contacts, collaboration among the various parties evolved to commercialize lesquerella as a new industrial oilseed crop. This effort involves two USDA-ARS laboratories—USWCL, Phoenix, and NCAUR, Peoria; the USDA Office of Agricultural Materials; and the two private companies. Major funding to support the joint effort was sought and successfully received in 1993 from the new USDA Alternative Agriculture Research and Commercialization (AARC) Center. The primary thrusts of this new funding are to provide support for the development of the infrastructure for breeding and production of planting seed by Mycogen Plant Sciences; the collection, evaluation and enhancement of germplasm by the USWCL; for research on improvement of oil extraction and utilization of the oil and seed meal by the NCAUR; and the use and derivation of new products for the cosmetic industry by Flora Tech. Department of Defense funds have also been obtained to support the much needed agronomic research on establishment of field plantings and weed control, which will be chiefly conducted by cooperating state universities in Arizona, New Mexico, Oregon and Texas. Research on water usage and management will be continued by the USWCL utilizing base program funds.

4. Summary and Conclusions

Development of new industrial crops that are well adapted to arid environments significantly contributes to the agricultural economy and benefits the producer, processor, consumer, and environment. The production, processing, marketing, and consumption components of most major agricultural crop systems have evolved over a period of many years. The development of a new crop adapted to an arid environment usually presents additional challenges, opportunities, and constraints. The current domestication and commercialization of lesquerella (*Lesquerella fendleri*), a plant native to an arid environment in the southwestern United States, is a good example of the process. A major reason for selecting lesquerella is that it produces a unique hydroxy fatty acid in its seed oil, which industry can use for the manufacture of various high-valued products such as high performance lubricants and oil additives, corrosion inhibitors, coatings, plastics, nylons, resins, waxes, pharmaceuticals, and cosmetics.

Research to domesticate lesquerella was initiated by USDA-ARS at the U. S. Water Conservation Laboratory, Phoenix, Arizona in 1984. Initial success in germplasm development and crop production research attracted early attention of industry. Transfer of technology has now resulted in successful private/public interaction, involving close collaborative effort of USDA-ARS, USDA-CSRS, the new USDA Alternative Agriculture Research and Commercialization (AARC) Center, state universities, and industry to fully commercialize lesquerella as a new, arid-lands adapted, industrial oilseed. It is reasonable to expect that other unique new crops can be established following the model used to commercialize lesquerella.

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Allenrolfea Deserts In Western North America

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1. INTRODUCTION

Allenrolfea occidentalis is a mono-specific genus of the chenopod or goosefoot family that is native to western North America. This perennial, woody based plant is the dominant vegetation that characterizes a type of desert landscape in the Great Basin. The unique aspect of this species is that it is the most salt tolerant plant that inhabits arid environments, perhaps the most moisture stress tolerant plant in the world. Despite the uniqueness of this plant species, our interest is not solely in the plant itself, but encompasses the desert environments where it grows naturally.

2. PHYSIOGRAPHIC SETTING

During the Pleistocene, huge inland lakes formed in the Great Basin.[1] The filling of the lakes was in response to increased precipitation, but perhaps more importantly a reduction in evaporation in response to lower mean annual temperatures and increased cloud cover.[2] The physical structure of the Great Basin is similar to a collapsed arch with high mountain ranges in the central portion, and basins on the western and northeastern margins. The deepest pluvial lakes, Lahontan in the west and Bonneville in the east, accumulated from runoff from the margins of the basin and the central highlands. Lake Lahontan expanded until it covered 36% of the landscape in what is now northwestern Nevada and northeastern California.

Pluvial Lake Lahontan never spilled over the mountainous rim of the basin to drain to the Pacific Ocean. Therefore, all of the soluble salts that were washed into the basin were left in sediments when the lake rapidly dried at the end of the Pleistocene. Modern Pyramid and Walker Lakes in northern Nevada are relatively small refilled portions of the former Lahontan system.

1) Salt deserts

The relatively sudden drying of the pluvial lake basins at the close of the Pleistocene left vast expanses of high salt content sediments exposed to wind erosion.[3] Apparently from refuges that existed in portions of the basin during the pluvial lake period and from long distant migrations, a flora evolved to occupy the landscape exposed by the retreating lakes.

The exposed landscape is largely characterized by very fine textured sediments deposited under relatively deep water conditions.[4] The permeability of these sediments to water is very slow. Minor moisture events, especially snow, often evaporate or sublimate from the surface of the sediments without penetrating the soil. High intensity moisture events, characteristic of irregularly occurring summer thunderstorms, result in over-land flow for brief periods.

Much of the scant atmospheric moisture that penetrates the Great Basin is deposited in the uplands, due to orthographic lifting and cooling of the clouds. The physiographic position of the lake sediments in the bottom of basins, surrounded by much higher mountain ranges results in mid-latitude temperate deserts in the vast valleys. Temperature inversions in the basins during the winter result in very cold temperatures, a truly cold desert.[5] Tital atmospheric precipitation in the basins averages 10 to 12 cm annually, with great variation among years. During drought years precipitation may hardly exceed 2 cm. The precipitation largely occurs in the cold winter months, out of phase with temperatures conducive for plant growth. Summer precipitation from thunderstorms is highly variable among years and in distribution within years.[6] Essentially the desiccated pluvial lake basins have become a desert from lack of atmospheric precipitation. What moisture does fall is largely un-available for plant

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growth because of cold temperatures and the accumulation of soluble salts in the soils which create osmotic deserts. The abundance of salts on the soil surface has led to the commom name salt deserts[7]. The combination of moisture, temperature and salt accumulations account for the three common names for this environment: cold, salt, or the modern scientifically accepted temperate deserts.

2) Landforms

The lowest surface elevation in northwestern Navada occurs at Pyramid Lake at near 1,200 m. The maximum level of Lake Lahontan was 1,348 m. Much of the floor of the Carson Desert, a major embayment of Lake Lahontan, is near 1,230 m in elevation.

Massive, often coalescing alluvial fans spill down from the rugged mountains that extend from 2,000 to 3,000 m around the basins. Wave action has often truncated the lower portions of these fans.[8] On the fans, the natural water table is so deep it never reaches close to the soil surface into the rooting zone of plants. The natural average depth of wetting, as indicated by the accumulation of calcium carbonate layers in the soil profile is usually around 15 cm. Most of the woody shrubs that characterize the vegetation of these landforms grow on sub-canopy mounds of accumulated subaerial deposition and saltation products. The mounds are about 15 cm high, effectively doubling the rooting depth. Leaf and fruit fall accumulate on these sub-canopy mounds creating the only litter on the soil surface in this environment. The only chance for nutrient cycling occurs in these litter accumulations.[9] The shrub mounds are surrounded by halos of the soil surface of various forms of microphytic crust.[10] The organisms that compose these crusts are important in nutrient cycling and fixation of atmospheric nitrogen.[11]

Depending on the magnitude of deflation of particular locations in the basins there can be areas of badland-type topography between the alluvial fans and the lake plain. Although highly variable in topography and vegetative cover, these areas can feature near vertically walled arroyos and slopes largely bare of vegetation.

The lake plains are immensely extensive in scale, sometimes extending for 75 to 100 km with slight variation. The plains step down from the base of the alluvial fans or badland escarpments in a series of nearly level plains separated by remnant off-shore bars and beaches.[12] The off-shore bars range in size from small escarpments less than a meter high, to well sorted gravel ridges 30 m wide at the base and several meters high. The larger bars often have wave plunge pits above and beyond the bar crest. These fossil lagoon areas have refilled with silt-textured subaerial deposition products and often support unique vegetation.[13]

The vegetation distribution of plant communities on the lake plain is highly variable, but closely related to the seasonal depth of ground water. Spring runoff from snow melt and rain in the surrounding mountains emerges from rock cut canyons on to the tops of alluvial fans and disappears in the relatively coarse textured material. The water percolates through the alluvial fan material until it strikes layers of fine textured lake sediments buried by the fans. The water travels laterally on top of the sediments and emerges on the lake plain more or less adjacent to the lower outline of the fan. The occurence of this ground water is very important in the soil and plant community development on the lake plain.

If the water comes all the way to the soil surface it will bring much of the soluble salt content of the soil profile to the surface. Usually, the water table drops on these sites during the fall and winter leaving white crusts of salts on the soil surface.

The effect of this seasonally rising water table is to allow a variety of phreatophytic plants to become esablished and allow their roots to follow the retreating ground water. The seasonal water table rise is highest near the margins of the lake plain and gradually decreases until the water table does not reach the soil surface. If there is an extensive area of lake plain before a significant drop in base level occurs with an off shore bar, the ground water table may never come in contact with the rooting of phreatophytic shrubs. At this point the vegetation will switch from phreatopytic to extremely drought tolerant shrubs that are dependent on atmospheric precipitation.

Eventually the lake plain drops off a final beach ridge into the lowest portion of the basin. If the basin is the terminus of a river originating in the surrounding mountains, an area of wet salt marsh occurs known as a sink. Compared to the surrounding lake plain, these can be very biologically diverse environments. In order to support vascular plants, these areas have to periodically dry and the accumulation of salts must be at least partially removed by wind erosion.

Much more extensive in area are flat, vegetation free areas, with polygons of salt effected lake sediments exposed on the surface. In North America these areas are known by the term playa. Depending on the extent of the basin, they may be a few to several hundred thousand hectares in extent. They occasionally will flood from exceptional moisture and runoff events. Sometimes lakes will persist for several seasons on portions of the playa. Under such conditions they will be driven across the playa surfaces by winds, and pile up against lake shores to considerable depth.

3) Plant communities

Dwight Billings enumerated the general plant communities and landforms of the Carson Desert of the pluvial Lake Lahontan basin during the 1940s.[14] The alluvial fans support sparse stands of shadscale (*Atriplex confertifolia*) and Bailey greasewood (*Sarcobatus baileyi*) with varying amounts of a few other woody species. The gross vegetation is often referred to as the shadscale zone even though Bailey greasewood is often the most abundant species.

The lake plain supports several plant communities that range from complex to simplistic. Where the ground water reaches the soil surface, a complex community consisting of black greasewood (*S. vermiculatus*), basin big sagebrush (*Artemisia tridentata* subsp. *tridentata*) and salt rabbitbrush (*Chrysothamnus nauseous* subsp. *consimilis*) occurs in apparent random swirls across vast landforms.[15] The dominant herbaceous vegetation in this community is basin wildrye (*Leymus cinereus*) in the drier areas and desert saltgrass (*Distichis spicata*) in the wetter areas.

As the distance from the truncated alluvial fans increases, black greasewood becomes the dominant shrub with only saltgrass in the understory. In areas where the ground water never reaches the rooting zone the landscape is characterized by shadscale plant communities.

There is great variability in the size and nature of the alluvial fans and the watersheds that constitute the origin of the fans. Occasionally the basin big sagebrush-black greasewood-salt rabbitbrush plant communities extend to the edge of the barren playa and conversely, occasional shadscale communities reach from the playa to and upon the alluvial fans. This is apparently a function of the presence or absence of fluctuating ground water.

There are a multitude of different types of playa surfaces. The surface characteristics have been studied bacause they provide natural runways for military airplanes and the space shuttle. A few of the playas have crystalline salt surfaces.[16] Much more common are surfaces composed of polygons of very fine textured deep water deposited sediments. Israel Cook Russell likened these surfaces to the finest Italian mardle in texture and uniformity. When they emerge from periods of flooding, the playa sediments support a crinkled expanse of mud curl. Following wetting by a brief moisture event, the polygons dazzle with crystalline evaporative salts.

Mud curls and salt crystals are easily eroded by winds. The vast expanses of vegetation free playa are obviously exposed to wind erosion. During the winter, contrasting low and high pressure systems are associated with wind direction. Low pressure brings winds from the southwest, followed by high pressure and predominantly north winds. The combination results in deposition on the northeast side of playas. If a fossil or modern stream deposits coarse textured sediments on a portion of the playa, ranges of Sand dunes are found on the northeast side of the playa. A much more common feature is parallel ranges of mud dunes. These are composed of salt crystals that cement the clay particles together to form a structure that behaves aerodynamically similar to sand grains. The general aridity of the climate near the playa preserves the structure of the mud dunes, but an occasional moisture event causes miniature glaciers of dissolved salts to flow down the dune topography.[17]

Springs are an important feature of the lake plain and playa topography and plant geography. Springs are very rare in most of the Lahontan Basin, but when they occur they are often geothermal. Often the combination of mineral rich hot water rising through very high salt content sediments results in evaporation around spring mounds that may be very rich in specific ions.[18] Subsequent wind erosion enriches entire basins.

3. ALLENROLFA DESERTS

The multi-million hectares of salt deserts in the Great Basin are distributed in some 190 basins separated by islands of moderate to towering mountain ranges. A recurring plant community in a small portion of the vastness of the salt deserts is that dominated by *Allenrolfea occidentalis*. The uniqueness of this community is the occurence of a woody based, long lived perennial plant growing in an environmental setting beyond the potential of almost any other species in a gross desert ecosystem dominated by salt tolerant species.

1) Study area

Our study site is located in Eagle valley about 80 km northeast of Reno, Nevada in the Carson Desert (Lat. 39° 45′, Long. 119° 15′). the valley is an elongated basin, extending north to south between Fireball Ridge (2,153 m) of the Truckee Mountains on the west and the Hot Springs Mountains (1,538 m) on the east. The south end of the valley is blocked by coarse-textured sediments from a fossil delta of the Truckee River when it was a glacially fed tributary of pluvial Lake Lahontan. The allenrolfea communities studied occupy an embayment on the north eastern portion of the valley. The elevation of the study site is 1,243 m or about 100 meters below the maximum elevation of pluvial Lake Lahontan. Our studies at this location were designed to evaluate the physiographic setting, community structure, soil, plant physiology, and seedling recruitment of *Allenrolfea occidentalis* plant assemblages.

Sereno WATSON, the botanist with the king's 40 th parallel survey, collected plants in the valley in the 1860 s and probably first collected allenrolfea in the communities we studied.[19] I. C. RUSSELL visited the site in 1880 and reported the numerous flowing salt wells along the northeast side of the playa, supported a large scale salt recovery operation where evaporators produced 100 tons of sodium chloride per hour on a warm summer day.[20] The salt was used in the reduction of silver ores.

The allenrolfea communities at the study site occupy about 1,000 ha. The communities are distributed continuously, with inclusions of stable sand dunes that rise 5 to 10 m above the lake plain.

The lower margin of the allenrolfea communities is clearly defined by the edge of the vegetation free playa. The transition from the playa to allenrolfea communities ranges from nearly level to a 1 m escarpment, apparently created by past wave action. From the playa edge to the back edge of the allenrolfea communities there is a rise in elevation of less than a meter over a distance of 5 km. The lateral margins of the communities are defined by sand dunes. The up slope margin of the communities does not have a distinct physiographic boundary, but there is an abrupt change from allenrofea to black greasewood dominance.

The allenrolfea plant communities are very simple, with only four woody and one herbaceous plant species represented (Table 1). Allenrolfea is the most abundant species, but the low, matlike growth form of this species in comparison to the 0.5 to 1.0 m high black greasewood and Torrey saltbush (*atriplex torreyi*) tends to blur the visual appearance of the stands and under emphasizes the aspect dominance of allenrolfea. In our sampling procedure, consisting of 40 macro plots 0.1 ha in area, allenrolfea was the only species with 100% constancy. Desert saltgrass averaged only 7% cover in the sample plots, but the cover of this creeping rooted grass ranged from

Table 1. Species composition, density per hectare, and constancy (percentage of stands where species occurred) of woody plant species in *Allenrolfea occidentalis* communities in the Carson Desert, Nevada.

Species	Density	Constancy
	number/ha	%
Allenrolfea occidentalis	230	100
Sarcobatus vermiculatus	10	80
Atriplex torreyi	20	55
Atriplex confertifolia	5	10
Kochia americana	1	1

0 to 100%.

2) Mounds

Virtually none of the vegetation in the allenrolfea communities is rooted in the playa sediments. Most of the woody plants are rooted in the mounds that dot the playa surface. The Eagle Valley allenrolfea communities average 260 mounds/ha. The number of mounds per hectare ranged from 0 to 590. This exceeds the density of allenrolfea plants so there were some mounds either bare (less than 1%) or occupied by other shrubs. Most of the mounds are from 1 to 2 dm in height (Table 2). A few of the mounds exceeded 1 m in height. The height of the mound does not appear to have any successional significance, but rather is related to the subaerial deposition or volume of saltation in different physiographic areas in the communities.

Table 2. Percentage distribution of allenrolfea mounds by height classes.

Height classes					
1 to 2	2 to 4	4 to 6	6 to 8	8 to 10	Greater than 10 (dm)
63%	21%	7%	5%	3%	1%

The playa sediments at Eagle valley are at least 50% clay sized particles. Many of these particles are fused and altered diatom tests. The mounds are composed of much coarser textured particles. Classical desert ecological theory maintains that the vegetation is restricted to the mounds because the soluble salts have been leached from the coarser textured mound soils. Robert BLANK determined in Eagle Valley that the mound soils have a higher salt content than the playa sediments (Table 3). Bio-enrichment from plant concentration of salts is thought to be the source of the salt accumulations.[21] Debra PALMQUIST and BLANK collaborated in developing three dimensional Kriging techniques to follow spatial variability in soil characteristics corresponding to the distribution of allenrolfea plants in the communities.[22]

In order to extract moisture from the inter-

Table 3. Saturation extract values of soil samples from growth sites of component species and topographic positions in *Allenrolfea occidentalis* community.
Adapted from BLANK, R. R., D. E. PALMQUIST, and J. A. YOUNG (1992). Plant-soil relationships of greasewood, Torrey saltbush, and allenrolfea that occur on coarse textured mounds on playas. pp. 194–197. *In* Symposium on the Ecology and Management of Riparian Shrub communities. General Tech. Report INT-289, USDA. Forest Service, Odgen, UT.

Growth site/topography	Electrical conductivity (ds/m)	Chloride (μg/ml)	Sodium (μg/ml)
Bare dune	120a[1]	56,000a	33,000a
Interdune	60b	20,700b	14,700b
Playa beneath dune	40b	14,500b	11,600b
Black greasewood	110a-c	51,800a-c	30,800a-c
Allenrolfea	60bc	21,200b	15,800bc
Torrey saltbush	60bc	21,100bc	14,300bc
Sea water[2]	—	19,000	10,500

[1] Means within the same column followed by the same letter are not significantly different based on Fisher's protected LSD at the 0.05 level of probability.

[2] Seawater data from *Bandbook of Chemistry*, 64 th Edition, CRC Press, Inc., Boca Raton, Florida. p. F-154.

face between the coarser textured mounds and the playa sediments, the allenrolfea plants have to allow salts to enter through root membranes. The phyto-toxicity of these salts is overcome by forming oxalates.[23] The salt desert plants dispose of salts through leaf and fruit fall or directly from glands.

Blank proposes that the mounds on the playa surface that predominantly support allenrolfea plants are successionally dynamic. A seedling somehow (see later section on seed germination) establishes on the playa and coarse textured particles eroding across the playa surface begin to accumulate around the seedling. Gradually the mounds build with seasonal burial of the allenrolfea plants. The plant roots extract moisture from the area of the mound. Excavation of mounds showed that few roots of allenrolfea penetrate into the playa sediments. Allenrolfea is not a phreatophytic species in that the roots reach down to the ground water. The roots may exploit a perched water source in the area beneath the mound, but on top of the impervious playa sediments. In order to use this highly saline water the allenrolfea plants accumulate salts. These salts are lost in leaf fall which gradually enriches the salt content of the mound. We have counted 120 rings on the cross sections of allenrolfea stems at the soil surface. The centers of the stems are always lost to the activities of insect larvae. We do not know that the growth rings represent annual cycles, but it appears the plants are relatively old. The mounds are certainly to saline for seedling establishment, but they may eventually become to salty for the growth of allenrolfea established plants. Plant death results in eventual erosion of the mound. If this scenario is correct, the mortality rate in the stands we sampled is very low, but seed recruitment is zero.

Besides excavation of mounds, the root growth of allenrolfea was followed with inclined glass tubes placed in the mounds to form miniature rhizotrons. Root growth was measured using a fiber optic system. Allenrolfea roots begin growth late in the season after most other species have ceased root growth.

Calcium carbonate accumulations in soil horizons (k horizons) are used as tools in interpreting the age of soils and in understanding Pleistocene and Holocene climatic changes. These soil horizons are thought to evolve via additions of $CaCO_3$ supplied by eolian dust. Plant cycled calcium oxalate may be an important vector for calcium cycling in arid environments.[24]

3) Allenrolfea phenology

In the temperate deserts of northwestern Nevada, allenrolfea plants drop their leaves and become dormant during the winter. The stems are continually buried by moving particles on the surface of the dunes. The woody stems under the surface of the dunes are quite coarse (2 cm in diameter). In early spring buds begin growth beneath the soil surface. As the new branches elongate they are surrounded by short scale-like leaves. The elongated shoots are succulent and translucent. If you cut one of these translucent stems a hemoglobin-like red sap appears on the cut surface. Once the stems break, the surface the leaves become green. Later in the summer, the lower leaves may suddenly turn brown and dehisce. This may be in response to excessive accumulations of soluble salts.

Flowering occurs in late August and seed production is abundant even during very dry years. The seeds dehisce in late September to early October.

4) Leaf morphology

Light and scanning electron microscope studies of leaf cross sections show the leaf surface to be covered with expanded, hollow cells. The stomata are sunk well below the leaf surface. The vascular bundles in the leaves have thick cell walls reinforced with spiral ridges. The sunken stomata can increase resistance to water loss and may condition an overall increase in water use efficiency for allenrolfea.[25]

5) Eco-physiology

Simultaneous measurements of photosynthetic rate and stomatal conductance were made in the field at several significant phenological stages. Jim Trent compared allenrolfea and black greasewood. The two species had similar photosynthesis rates, but allenrolfea had higher water use efficiency. Maximum photosynthesis occurred in the morning at temperatures below 30℃, for both species. Afternoon temperatures measured in the photosynthesis cuvette reached 38℃. The pre-dawn xylem potential of allenrolfea plants was extremely negative, but never as low as the water potential of the soil solution beneath the mounds.[26]

6) Seed germination

Considering the extreme salt concentrations in the surface of seedbeds in the allenrolfea communities the process of seedling establishment is of obvious interest. The seeds of allenrolfea germinate readily at a wide range of con staut and alternating temperatres (Table 4). The seeds are extremely viable for material produced under natural conditions in a harsh environment. Robert Blank investigated the germination of allenrolfea seeds in reduced

Table 4. Estimated percentage germination and one-half the confidence interval derived from a quadratic response surface for seeds of *Allenrolfea occidentalis*.
Seeds incubated at 55 constant and alternating temperatures for 4 weeks. Adapted from Blank, R. R., J. A. Young, Ellen Martens, and D. E. Palmquist (1994). Influence of temperature and osmotic potential on germination of *Allenrolfea occidentalis* seeds. *J. Arid Envionments* (in press).

Cold period 16 hr (℃)	Warm period 8 hr									
	0	2	5	10	15	20	25	30	35	40 (℃)
0	3 (6)	16 (5)	33 (4)	57 (4)	74 (4)	84 (4)	88 (4)	85 (4)	75 (5)	59 (7)
2		15 (5)	33 (4)	57 (3)	75 (4)	87 (4)	92 (4)	90 (3)	81 (4)	66 (6)
5			30 (5)	57 (3)	76 (3)	89 (3)	96 (3)	95 (3)	88 (3)	75 (5)
10				51 (5)	73 (3)	89 (3)	98 (3)	100 (3)	96 (3)	85 (5)
15					65 (5)	84 (4)	95 (3)	100 (3)	99 (4)	91 (5)
20						73 (5)	87 (4)	95 (3)	96 (4)	90 (5)
25							74 (5)	84 (3)	88 (3)	85 (5)
30								68 (5)	74 (4)	74 (5)
35									56 (6)	58 (6)
40										37 (8)

Table 5. Estimated percentage germination of *Allenrolfea occidentalis* seeds under reduced osmotic potentials created with salts of polyethylene glycol (PEG) solutions.
From Blank, R. R., J. A. Young, Ellen Martens, and D. E. Palmquist (1994). Influence of temperature and osmotic potential on germination of *Allenrolfea occidentalis* seeds. *J. Arid Environments* (in press).[1]

Osmoticum	Osmotic Potential (MPa)							Coefficients of determination (R^2)
	0	−0.2	−0.8	−1.6	−2.4	−3.0	−4.0	
$NaNO_2$	42G–N	35J–Q	17U–X	1Y–1	01	01	5Y–1	0.76
$CaCl_2$	63A–D	63A–C	61A–D	52C–G	39H–N	25P–U	0Y–1	0.86
$MgSO_4$	74A	68AB	51D–G	32M–R	17T–X	8W–Z	0Y–1	0.89
Na_2SO_4	66AB	58B–F	38J–N	17U–X	4Y–1	0Z1	0Y–1	0.92
PEG6000	56A–J	58A–G	60A–G	56A–H	44D–O	29L–U	0X–1	0.60
NaCl	59A–G	59A–F	55B–G	46E–M	33K–S	19R–X	0Z1	0.78
KCl	68AB	66AB	57B–F	44G–M	29N–T	17TX	0Y–1	0.87
KNO_3	62A–E	58B–F	47F–K	33L–R	21Q–W	12V–Y	0Y–1	0.82
$(NH4)_2SO_4$	57A–I	51B–L	36H–Q	21O–X	14S–Z	12U–Z	17N–1	0.50
$NaNO_3$	59A–G	60A–F	61A–D	56B–G	45F–M	31M–S	1X–1	0.75
$MgCl_2$	65A–D	62A–E	51C–H	36I–P	22P–V	12U–Y	0Y–1	0.82

[1] Estimated germination values from regression equations followed by the same letters (A–Z then 1–9) are not significantly-different based on overlap of the confidence intervals at $P \leq 0.05$ level.

Table 6. Total soil water potential (MPa) of soil from *Allenrolfea occidentalis* seedbeds located at Eagle Valley, Nevada from December 1991 through November 1992.

Collection microsite	Month										
	Dec.[1]	Jan.	Mar.	Apr.	May	June	July	Aug[1].	Sept.	Oct.	Nov.
Mound	−25	−43	−41	−35	−63	−106	−111	−72	−99	−54	−49
Playa interspace	−25	−36	−41	−33	−41	−63	−86	−36	−37	−46	−37

[1] Samples collected soon after large precipitation event.

osmotic potentials created with polyethylene glycol solutions or solution of various salts (Table 5). Allenrolfea seeds had germination at the extreme osmotic potentials of -3 to 4 MPa. However, when BLANK compared the potential of allenrolfea seeds to germinate under reduced osmotic potentials with soil water potentials in field seedbeds, there was no overlap (Table 6).[27]

In later studies of the seedbanks of allenrolfea, it was determined that prolonged leaching of the seedbed soils was required before natural or spiked seeds would germinate. The only natural allenrolfea seeds that could be detected in seedbanks were found in the nest of saline harvester ants (*Pogonomyrmex salinus*).[28]

We are left with repeating the often used theme for germination and establishment of extreme halophytes that establishment must occur at some rare interval when some unknown environmental condition raises the osmotic potential of seedbeds. Just what this unknown environmental condition is and when it occurs is a matter of extreme speculation for allenrolfea communities.

7) Lessons to be learned from allenrolfea

Plant growth is possible under extreme osmotic stress if the plants equalize osmotic potentials through uptake of salts without phyto toxicity. In the case of allenrolfea this trait probably imparts immunity to herbivory, but not granivory. Seedling recruitment is apparently extremely episodic. Restoration of a damaged allenrolfea environment would be extremely difficult.

4. Summary

The mid-latitude temperate deserts of western North America offer many examples of plant adaptation to atmospheric drought and salt induced moisture stress. Plant communities dominated by *Allenrolfea occidentalis* offer the extreme in adaptations to survival and growth under moisture stress. These plants produce abundant viable seeds with the potential to germinate under extremes in temperature and greatly reduced osmotic potentials. However, the seeds are not capable of germinating under the current seedbed conditions that exist in nature. This finding has application to the germination ecology of many halophytes.

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Effect of Super Absorbent Polymer on Water Movement in Soil

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1. Introduction

The desertification is one of the most important global environmental issues. Desert area has been expanded for several decades. This is not only caused by the climate change, but also by such artificial destruction of ecosystem as overgrazing, inadequate cultivation, deforestation and inappropriate irrigation.[1]

The inappropriate irrigation may often cause salt damage through an accumulation of the salt in the soil by rising underground water.[2,3] The desertification by salt damage can be often seen in irrigation-based area in arid region. The countermeasures against the salt damage have so far been proposed and carried out. In the conventional irrigation techniques, the pass ways for irrigation water and drainage are constructed and salt leaching through water flow are also conducted.[4] In the former, the underground water level is lowered through pumping of water from drain stream. However, these techniques need ample supply of water. Their use results in a rising underground water level so that water from soil surface reaches underground water level and salt damage is promoted. Their techniques have both effective and ineffective aspects.

In sprinkler or drip irrigations, different from the conventional techniques, less water is poured out on the soil surface. These techniques posses less drawback of the excess irrigation. Recently, use of super absorbent polymer (SAP) with drip irrigation has been focussed as a promising irrigation technique.[5] In implementing the above methods, it is important not only to take the establishment of irrigation and drainage pathways into account but to estimate and quantitatively describe the water and salt movement in soil.

In this paper, the distribution of water in one-dimensional apparatus filled with glass beads is studied to predict the behavior of water in soil or sand in arid land. The effects of SAP on water movement in soil under the initial conditions for the cases stipulating dry and rain seasons are experimentally investigated. In addition, a conceptional model is proposed for explaining the difference in water movement in soil between the two cases.

2. Experimental

The two types of one-dimensional apparatus used in this study are shown in Figs.1(a) and (b). They were made of acrylic resin and were filled with spherical glass beads of 350–500 μm in diameter with or without 0.1 wt% SAP (20–145 mesh: 95%, AP-100 from The Nippon Synthetic Chemical Industry Co., Ltd., Osaka. Japan). The heights of the bed were 260 mm for the apparatus (a) and 270 mm for the apparatus (b). The apparatus (a) had 18 sets of sampling holes. Small amounts of samples were obtained through the holes at adequate intervals, and then filled with the same amount of beads with or without water saturation. The apparatus (b) could be separated into nine pieces with the height of 3 cm. Though this apparatus did not enable successive sampling of the glass beads, more accurate data on water content were obtained because of no replacement of the glass beads samples.

The apparatus were put on trays filled with water up to the depth of 10 mm. Under the wet condition experiments to stipulate the seasonal rain, the entire apparatus was dipped into the water used in the experiments. The experiments were conducted under constant temperature of 25℃ and relative humidity of 25%.

The water movement was estimated by the change of local water content in the bed sampled at regular time intervals. The local water

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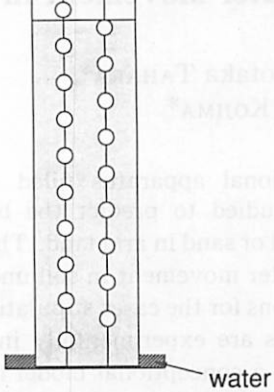

Fig. 1(a). Outline of appartus.
wide 60 mm; deep 20 mm; height 300 mm
Glass beads diameter 0.4 mm.

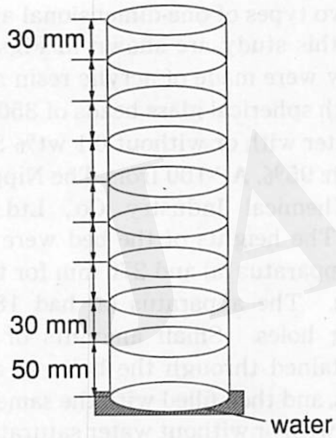

Fig. 1(b). Outline of apparatus.
Inside diameter 50 mm; Height 290 mm
Glass beads diameter 0.4 mm.

content was determined from the weight loss of glass beads bed samples by drying. In the case of the apparatus (a), the glass beads were sampled as follows. Thin tubes made of plastic sheets were inserted into the sampling holes to cut the bed. By pushing out glass rods into the thin tubes, the glass beads samples fell into the thin tubes. At the height below the water level by capillary force in the bed, fresh glass beads with soaking in water were filled again into the sampling holes, while at the height above that, fresh glass beads were filled. In the case of the apparatus (b), the glass beads were sampled by

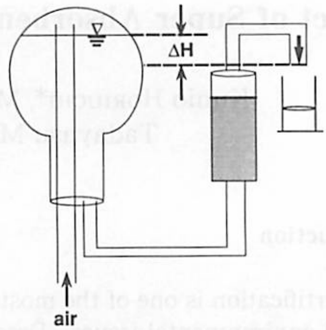

Fig. 2. Outline of apparatus for water permeability.

dividing the apparatus into nine pieces by cutting with a thin knife. As expected, the SAP swelled by the absorption of water and consequently clogged the gaps among the glass beads. The effect of swelling on the water permeability through the layer of glass beads was also studied at the appropriate pressure differences. The apparatus used in this experiment is shown in Fig. 2.

3. Results and Discussion

1) Profiles of the water content without SAP under the wet and dry conditions

When the apparatus was placed on the tray filled with water, the layer of glass beads, with and without SAP, was divided into three parts: a part lower than a height where water level raised by capillary action (hereafter, abbreviated as capillary height), a part where water and steam coexist, and a part without water. The capillary height reached up to the height of approximately 90 mm above the water level filled in the tray.

Under the wet condition simulating the drainage of water by the seasonal rain, i.e, condition that water level rose, the profiles of the water content without SAP are shown in Fig. 3. In the apparatus (a), the data on water content had variances, and furthermore, the water content after 25 days was lowest. These phenomena may be explained by the stipulation that the water content profile was disturbed because the glass beads samples were successively replaced with fresh glass beads. These may also be expected from the vaporization and

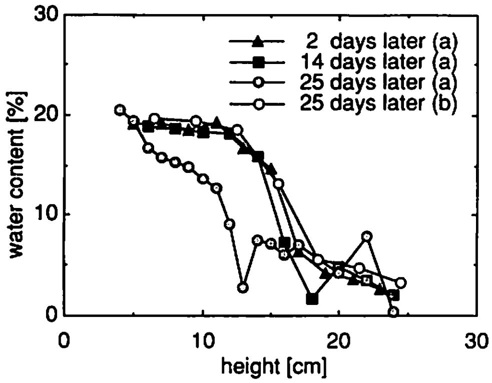

Fig. 3. Profile of water content.
wet, without SAP, water.

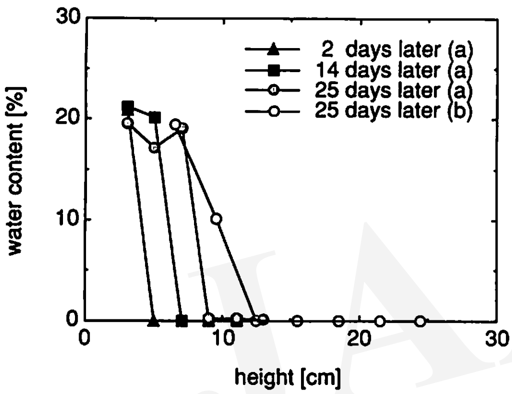

Fig. 4. Profile of water content.
dry, without SAP, water.

successive condensation of water in bed. However, the decrease in the water content was not caused by the vaporization of the layer because the water content profile in the apparatus (b) was similar to those measured in the apparatus (a) except the data for 25 days later. From the above discussion it could be concluded that the profile of the water content under the wet condition without SAP attained a steady state only after two days or less.

Under dry condition simulating the dry season the profile of the water content without SAP is shown in Fig. 4. The profiles of the water content in the apparatus differed from those under the wet condition. This indicates that the water content is under an unsteady state. Furthermore, the water content in apparatus obviously increased as time elapsed. In the present case the experimental problem for the wet case was not as serious because the data from apparatus (b) after 25 days generally agreed with the extrapolation of the data sets of 2 and 14 days. The small difference between for apparatus (a) and (b) at 25 days after may be caused by the interference of the water movement due to the replacement of the glass beads samples in apparatus (a). It can be considered that after the start of the experiment under dry condition, the change of the water content profile was caused mainly by the water movement due to the evaporation of water followed by the condensation of steam. It was difficult to get a steady state from the profile under the dry condition, because the change in the water level due to the condensation of steam was extremely slow. These results indicated that the observed steady state from the wet condition may be the apparent one considering the capillary force, and the intrinsic steady state with vaporization and condensation may exist between the results of the wet and dry conditions.

2) Effect on SAP of the water content under the wet condition

Figure 5 shows the profile of the water content with SAP under the wet condition. In the case of the glass beads mixed with SAP, the water content after 25 days was larger than that without SAP at each height in the layer. The difference in the water content measured for the various heights of bed was thought to result from the difference in the condition of SAP absorbing water. The holdup of the swelled SAP in the column was remarkably affected with the amount of water absorbed with SAP because the volume of absorbed SAP increases with its amount. As small variation below the height of 12 cm was observed because the area was located under the capillary height and enough water was supplied; however, the slow water movement caused by the blockage due to the expansion of SAP with its swelling may caused difference in the water content between the results for apparatus (a) and (b). The discussion is conducted on the water contents above and below the bed height of 12 cm which was the capillary height observed under the dry condition and/or without

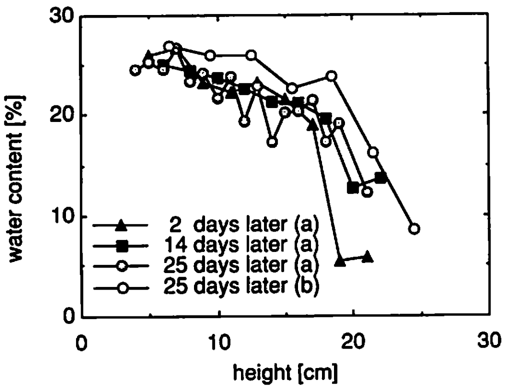

Fig. 5. Profile of water content.
wet, with SAP, water.

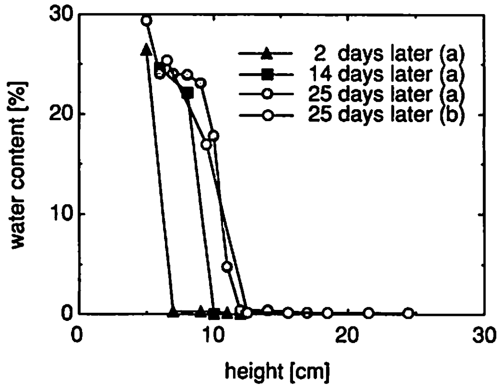

Fig. 6. Profile of water content.
dry, with SAP, water.

SAP.

The difference between the results in Fig. 3 without SAP and Fig. 5 with SAP is discussed. The water content with SAP was larger than that without SAP by about 5% for those below the height. For those above the height the water content with SAP was larger than that without SAP by 10%. The difference above the height was thought to appear because the both the water movements by drainage in short period and by drying the water held between beads were prevented by the SAP. The clogging of clearance between the beads may also prevent steam from transportation. It was found that the layer with SAP constantly kept more water content than that without SAP.

3) Effect on SAP of the water content under the dry condition

The profile of the water content for the case of the layer mixed with SAP under the dry condition is shown in Fig. 6. While the tendency in the change of the profile of the water content with SAP was similar to that for without SAP under the dry condition, the water content for the case of the layer with SAP was lager than that without SAP at each water level as for the wet condition. Furthermore, the rising rate of the water with SAP was higher than that without SAP, while the maximum height containing water after 25 days was nearly equal at around 12 cm. The difference in the water content in the apparatus (b) between with SAP and without SAP was caused by rising water content owing to absorption with SAP at the upper water level. SAP kept the water content and prevented water from vaporizing above water level due to swelling and clogging to the gap among the glass beads.

In comparison of the results with SAP in Fig. 5 for wet condition and Fig. 6 for dry condition, the water content below the capillary height in Fig. 6 was as large as that under the wet condition, while that around and above the capillary height was extremely smaller than that in Fig. 5, because the drainage water was not added into the apparatus under the dry condition and SAP could not absorb water above capillary height. These results also suggested that the water movement was limited by swelling of SAP with water.

4) Effect of swelling of SAP on the water permeability through the layer of glass beads with SAP

In order to estimate the blockage by SAP swelling in the gap among the glass beads, the experiment on the water permeability through the layer of glass beads mixed with SAP was conducted with appropriate pressure differences by using the apparatus shown in Fig. 2. In this experiment, the water permeability through the layer was evaluated by the successive measurement of the flow rate of water. The difference in the content of SAP between 0 and 0.1 wt% in the glass beads remarkably

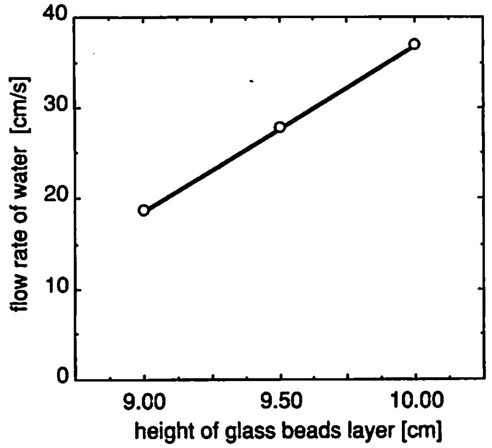

Fig. 7. Water permeability through the glass beads layer.

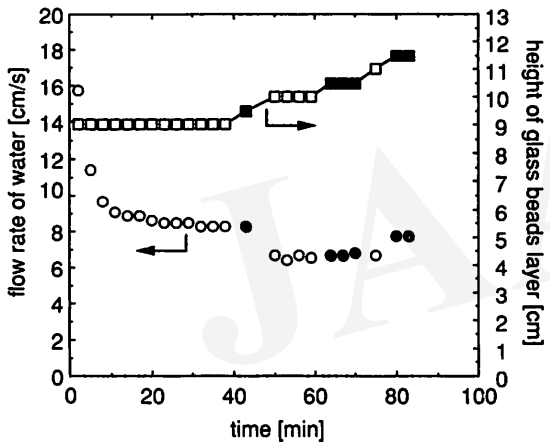

Fig. 8. Water permeability through the glass beads layer with SAP.

affected the blockage of the gap among the glass beads. The pressure difference between the storage vessel water level and the overflow level after column was determined at 10 cm. During this experiment, the glass beads height was first set at 90 mm and then expanded with 5 mm increment to 115 mm. In the case of the glass beads without SAP, the water permeability through the glass beads without SAP was reproducibly measured. The effect of the result on the water flow rate on the bed height is shown in Fig. 7. The water flow rate was increased with the layer height because the gap among the glass beads was expanded by the increase of the bed volume.

For glass beads with SAP of 0.1wt%, the water flow rate on the bed height was not reproducibly measured. The time variation of the rate is shown in Fig. 8 with the bed height chosen as an experimental parameter. The water flow rate was remarkably decreased at the beginning of this experiment while the bed height was kept unchanged. Further, it often decreased with the expansion of the glass beads layer in spite of the expected expansion of the gaps among the glass beads. The water permeability through the bed with SAP was not evaluated because of the complicated relation between the water flow rate and the pressure difference in the apparatus, which may be caused by the history of the bed. The difference in the time variation of the water flow rate between those without SAP and that with SAP was thought to be caused by the clogging of the gap among the glass beads by SAP swelling. It was concluded that SAP made the rate of the water rise and drain slow because the blockage of the water pass was caused by the expansion by swelling of SAP.

4. Conceptional Model

In order to predict the water content profile at the intrinsic steady state, a conceptional model is proposed for explaining the difference in water movement in soil between the wet and the dry conditions.

The layer of glass beads packed into the apparatus with some gaps is schematically shown in Fig. 9(a) and (a′) respectively for the wet and dry conditions. Water and steam move through the gaps in the layer. In a layer where water and steam coexist, water tends to gather in the gaps. The fact that the level of the water content under the wet condition is higher than that under the dry condition is understood. A model which describes such phenomena as above should be developed.

The model presented for description of the water movement is shown in Fig. 9(b) and (b′) respectively for the wet and dry conditions. It is made up of many tubes with various diameters in series. The total volume of the tubes in Fig. 9(b) is equal to that of the gaps in Fig. 9(a). The water level in the narrower part in the

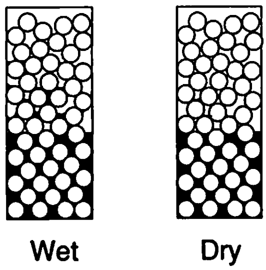

Fig. 9(a)(a′). Conceptional Models.

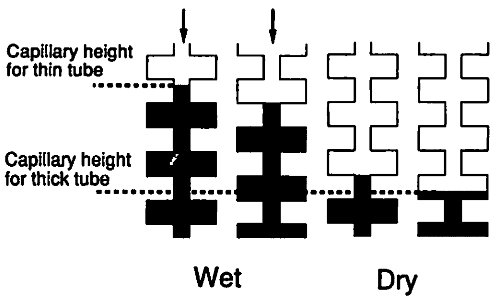

Fig. 9(b)(b′). Conceptional Models.

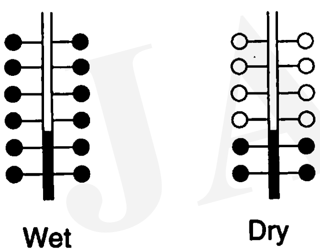

Fig. 9(c)(c′). Conceptional Models.

tubes are randomly arranged in the layer. The distribution of water content experimentally observed may be explained by the different capillary heights in the tube. The level of water content under the wet condition is higher than that under the dry condition because the drainage water under the wet condition stops at the capillary height of thin tube or at the top of the thin tube just below the level. Under regular condition the water content under dry and wet conditions may differ because the water stops at the capillary height or at bottom of the thick tube above water level.

In order to estimate the gathering of the water around the contact points of the particles in Fig. 9(a), the model shown in Fig. 9(c) is proposed. The model consisted of thin tubes with many small water storage parts. The thin tube diameter is equal to the narrowest diameter of tubes in Fig. 9(b). The total volume of the water storage parts and thin tubes in Fig. 9(c) is equal to that of the tubes in Fig.9(b). The water content in the thin tubes range from relative humidity of 100% at the capillary height to that of 0% at the highest level of water content. Under the wet condition, the decline of the water content above the capillary level is caused by the drying of the storage parts. Further improved model could be presented with the combination of the concepts demonstrated in Fig. 9(b) and (c).

5. Summary

The distribution of water in one-dimensional apparatus filled with glass beads was experimentally studied to predict the behavior of water in soil or sand in arid land under initial conditions stipulating dry and rain seasons. It could be concluded that the profile of the water content under the wet condition without SAP attained to a apparent steady state only after two days or less while that under the dry condition no results were apparent after 25 days.

The effects of SAP on water movement in soil were also investigated. It was found that the layer with SAP retained more water content than that without SAP. It was concluded that SAP increased the rate water rose quickly and drained slow because the blockage of the water pass was caused by the expansion of SAP with its swelling, from the experiment on water permeability through the layer of glass beads mixed with SAP.

Acknowledgement

We are grateful to the Sumitomo Foundation for support of this research.

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The Development of Permanent Isolation Barriers for Buried Wastes in Cool Deserts: Hanford, Washington

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Abstract

The Hanford Site Surface Barrier Development Program has been developed to design and test an earthen cover system (barrier) that can be used to inhibit water infiltration, plant and animal intrusion, and wind and water erosion. The barrier is designed to isolate buried wastes from environmental dispersion for at least 1,000 years. The Hanford Site is located in south-central Washington, which is characterized as a cool desert. Yearly precipitation averages 160 mm, falling mostly in the winter.

The prototype barrier design includes a fine-soil surface with a relatively high infiltration rate to limit infiltration below the fine soil by inducing temporary storage near the surface. Transpiration by vegetation and evaporation will return stored water to the atmosphere. A capillary break created by the interface of the fine-soil layer and coarser textured material below will further limit infiltration and promote evapotranspiration. Should water pass the interface, it will drain laterally on a low permeability asphalt layer through a coarse-textured sand/gravel filter layer.

Water infiltration control is a key component in barrier design. Lysimeter studies indicate that a surface layer of fine soil with deep-rooted plants precludes drainage even with three times normal precipitation. Drainage on the Hanford Site occurs when soils are coarse textured even when plants are present.

Studies at the Hanford Site have shown that plants and animals will significantly interact with the barrier. Plants serve to transpire soil water back into the atmosphere. Native deep-rooted (down to 3 m) perennials such as sagebrush and bunchgrasses will best recycle water, while shallow-rooted (~60 cm) introduced annuals such as cheatgrass can potentially lead to infiltration. Deep-rooted tumbleweeds potentially could intrude into the waste, but coarse rock layers and a redundant asphalt layer will prevent penetration. Animal intrusion studies indicate that small animal burrows have no significant effect on soil water storage, and that large animal burrows have a small effect in winter that disappears in spring or summer.

Current work tests our integrated scientific and engineering concepts on a large prototype barrier to determine if it can isolate buried wastes from environmental dispersion.

1. Introduction

Large amounts of radioactive and hazardous wastes are currently buried in shallow landfills at U.S. Department of Energy (DOE) facilities.[1] The Hanford Site contains 10.3% of all low-level nuclear waste in the United States.[2] Such wastes pose a potential threat to human health and to the environment.[3] Options for waste disposal include exhuming or isolating in place. A waste isolation option includes the use of surface cover systems. A major challenge in the development of surface cover systems or permanent isolation barriers is to design the barrier to ensure that buried wastes are isolated from dispersion by environmental forces for long periods of time.[4] In the case of radioactive wastes, the period of isolation has been suggested as being from at least 1,000 years,[5] to 10,000 years,[6] to 24,000 years[7] and up to millions of years.[8]

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The need for permanent isolation for extended periods of time means that special consideration of dispersal factors needs to be taken into account in the design of barriers. Factors that can disperse wastes into the environment include water, wind, plants, and animals. Water is the primary agent for dispersion of wastes into the environment and has been the primary cause of barrier failures.[6] As a consequence, arid environments where, by definition, water is scarce, have been proposed as the best location for siting waste repositories.[3, 7]

Research on the application of permanent isolation barriers to wastes at the arid Hanford Site, has been ongoing since the early 1980's.[9] It has been demonstrated that intrusion, by

Table 1. Permanent isolation barrier development task groups.

1.	Biointrusion control
2.	Water infiltration control
3.	Erosion/deposition control
4.	Physical stability testing
5.	Human interference control
6.	Barrier construction materials procurement
7.	Prototype barrier designs and testing
8.	Natural barrier analogs
9.	Long-term climate change effects
10.	Model applications and validation
11.	Interface with regulatory agencies
12.	Resource conservation and recovery act equivalency
13.	Technology implementation and transfer

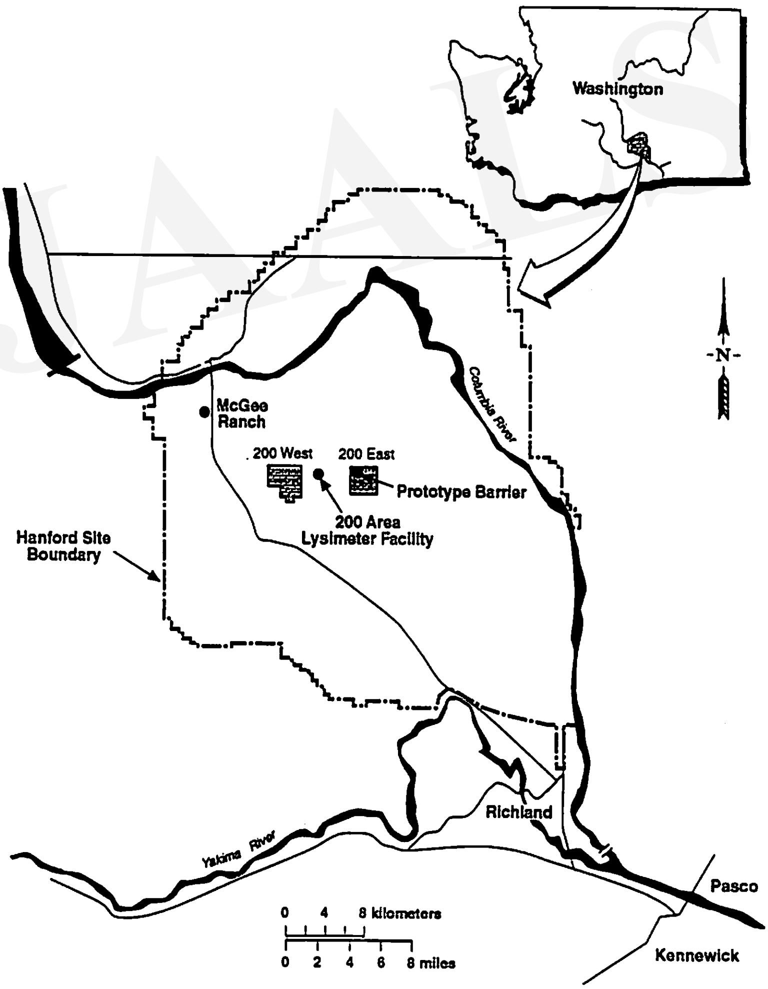

Fig. 1. Hanford Site map showing the location of McGee Ranch and the permanent isolation barrier in the 200 Area Plateau.

roots, animals, and ants, into buried waste could be prevented if a layer of loose rock covered with an asphalt emulsion was placed between the buried waste and the topsoil.[10] This soil structure, a fine top-soil over loose rock, also constitutes a capillary break.[11] Such a configuration limits downward water movement and tends to store water in the soil, where it can be lost to the atmosphere through evaporation and transpiration. The use of a capillary break is one of the major design features of the permanent isolation barrier and has been investigated extensively at Hanford.[12,13,14]

Plants and animals will have significant effects on the upper fine soil layer where they live and can, potentially, compromise the barrier. Thus, it is important to determine how plants and animals will affect the soil water balance, the stability of the surface subjected to wind and water erosion, and the potential for biointrusion into the waste.[9,15]

The purpose of this report is to present the results of research on surface hydrology and the role of plants and animals on permanent isolation barrier effectiveness at Hanford. These topics are a subset of a larger set of studies on permanent isolation barriers listed in Table 1. A complete review of these tasks has been documented.[16] We also discuss current work that tests our integrated scientific and engineering concepts on a large prototype barrier to determine if it can isolate buried wastes from environmental dispersion.

2. Site Description

The study area is on the United States Department of Energy's Hanford Site in south-central Washington (Fig. 1). The Hanford Site is 1,480 km^2 in area and varies in elevation from 120 to 1,200 meters above sea level (m.a.s.l.). The area has an arid climate with hot dry summers and cool wet winters. Average yearly precipitation is about 162 mm, falling mostly in the fall and winter.[17]

The McGee Ranch site (244 m.a.s.l.), from which barrier surface soils are obtained (Fig. 1), is dominated by shrubs (*Grayia spinosa* and *Artemisia tridentata*) with several species of forbs, perennial grasses, and the annual grass

Table 2. Typical particle-size analysis for soils at McGee Ranch. The United States Department of Agriculture classification is used for texture.

Depth (cm)	% sand	% silt	% clay	texture
2	49.0	41.5	9.5	loam
6	46.0	45.5	8.5	loam
12	33.5	51.5	17.0	silt/loam loam
20	19.0	66.0	15.0	silt loam
34	24.5	65.5	10.0	silt loam
60	19.0	67.0	14.0	silt loam

Bromus tectorum. The soils have been classified as Xerollic Camborthids such as Warden silt loams.[4] A description of soil characteristics is given in Table 2. A complete site description has been documented.[18]

The site where the permanent isolation barrier is to be built is located on the 200 Area Plateau at an elevation of 223 m.a.s.l. (Fig. 1). It has the same floral makeup as the McGee Ranch site with the addition of the shrub *Purshia tridentata*. The soils are coarse-textured alluvial sands covered by a mantle of wind-deposited fine sands of the Quincy soil series (mixed, mesic Xeric Torripsamments).[4]

3. Barrier Issues

Permanent isolation barriers use engineered layers of natural materials to form an integrated structure with redundant protective features. Natural construction materials such as fine soil, sand, gravel, riprap, and asphalt have been selected to optimize barrier performance and longevity. The main objectives of the barrier design are that the structure be maintenance-free, that wastes be isolated for a minimum of 1,000 years, that drainage be limited to near-zero amounts (0.5 mm yr^{-1}), and that the likelihood of biointrusion by plants, animals, and humans be minimized.[19]

The permanent isolation barrier (Fig. 2) consists of various materials placed in layers forming an above-grade mound over the waste zone. The design consists of a vegetated fine-soil layer overlying layers of sand, gravel, riprap, and asphalt. Each layer serves a dis-

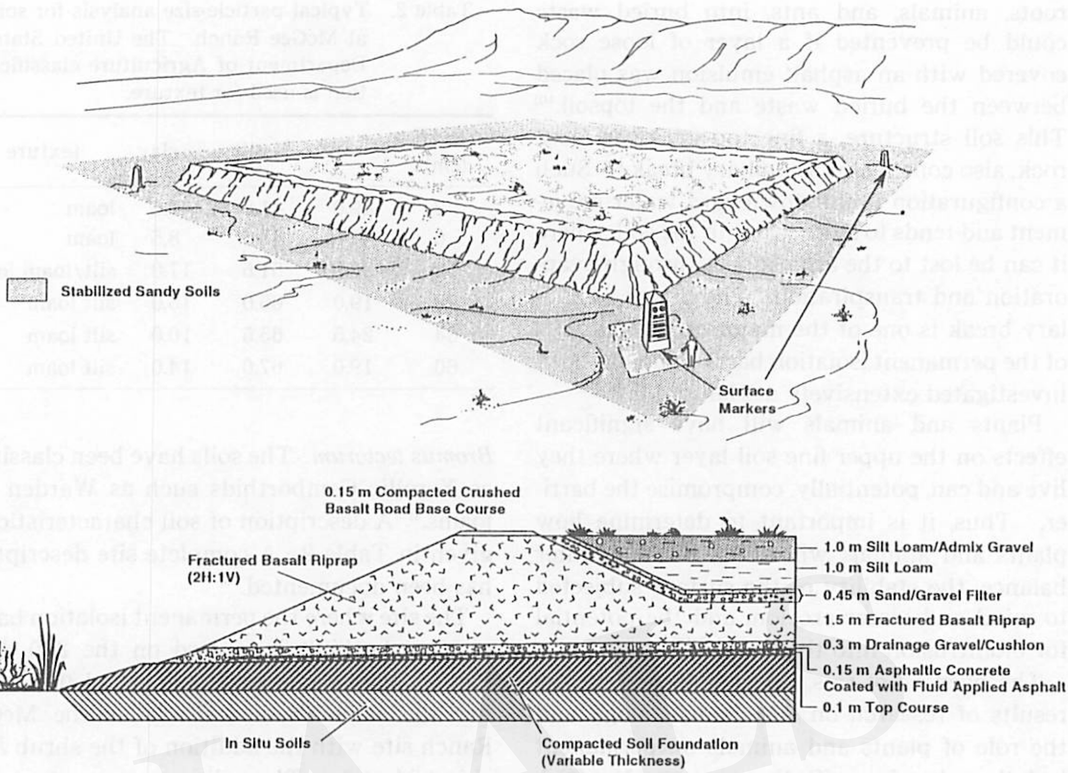

Fig. 2. Typical isolation barrier.

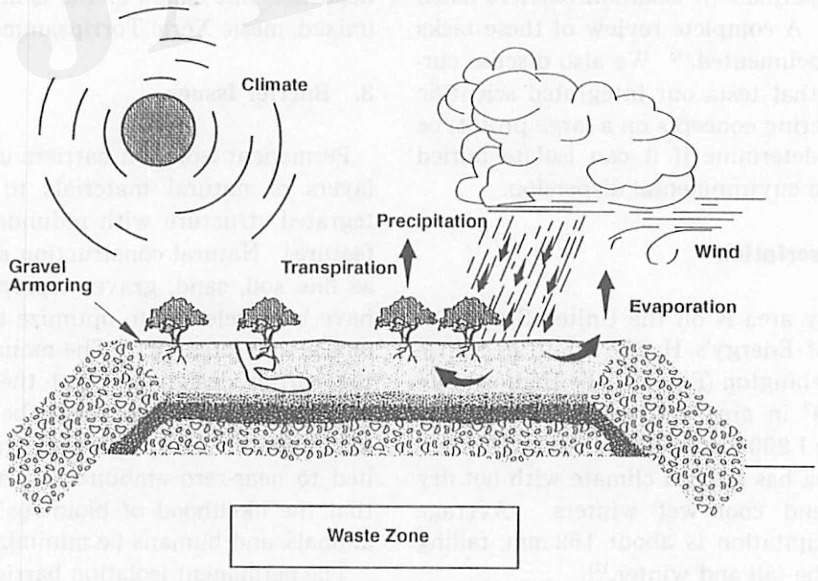

Fig. 3. Functional performance of barriers.

tinct purpose. The vegetated fine-soil layer acts as a medium in which moisture is stored until the processes of evaporation and transpiration return the water to the atmosphere (Fig. 3). The coarser materials (sand, gravel, riprap) below the fine-soil layer create the capillary break that inhibits the downward infiltration of water through the barrier. The coarse mate-

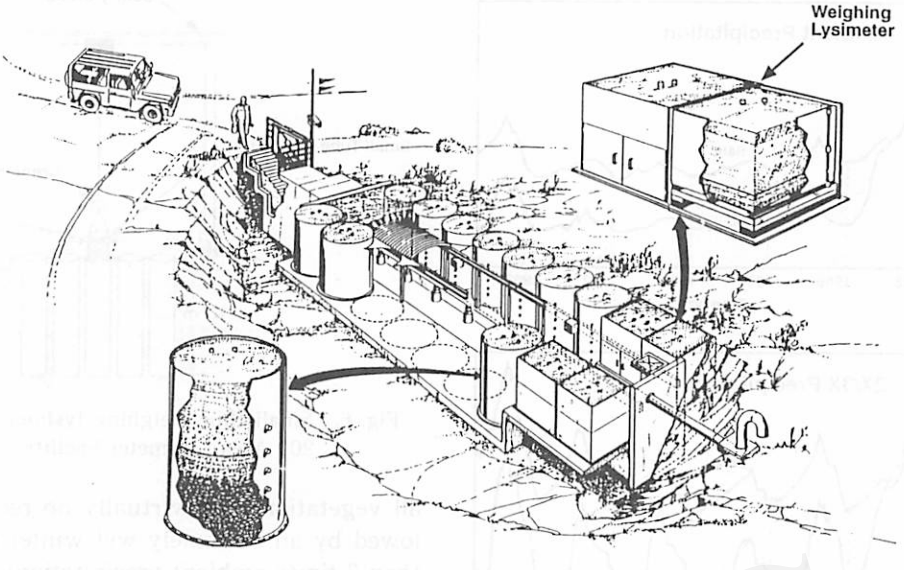

Fig. 4. Weighing lysimeters at the 200 Area Lysimeter Facility.

rials also inhibit biointrusion below the fine-soil layer. The asphalt layer will be placed below the coarse layers just above the ground surface. This layer will divert any water that gets through the capillary break away from the waste zone.

1) Surface hydrology

We will discuss the results of surface hydrology studies done at two sites. The first study examines the effectiveness of capillary break configurations using weighing lysimeters[14] and the second considers the effect of surface conditions on soil water storage in small tube lysimeters.[1]

The study of the effectiveness of capillary break configurations on soil water storage was conducted at the 200 Area Lysimeter Facility (Fig. 1). We tested the hypothesis that a thick fine-soil layer over coarse sands would prevent drainage under four treatment conditions: ambient precipitation non-vegetated, ambient precipitation vegetated, additional precipitation non-vegetated, and additional precipitation vegetated.

The weighing lysimeters are 1.5×1.5×1.7 m and contain about 5,900 kg of soil (1.5 m deep) placed on top of about 0.2 m of sand (Fig. 4). Vegetation consists of the deep-rooted evergreen shrub *Artemisia tridentata*, the deep-rooted perennial bunchgrass *Oryzopsis hymenoides*, the shallow-rooted perennial bunchgrass *Poa sandbergii*, and the shallow–rooted winter annual grass, *Bromus tectorum*. Precipitation treatments consisted of ambient precipitation and twice ambient precipitation (~320 mm yr^{-1}). In the last 3 years of observation, precipitation was increased to 480 mm yr^{-1}. Scale weights are recorded every 20 s and have been recorded since November 1987. To measure drainage, these lysimeters have sloping bottoms and a drain port at the low point.

The soil water storage dynamics of the four lysimeters from 1987 through 1993 are presented in Fig. 5. All four treatments exhibit a seasonal cycle of storage with maximum storage occurring in March after the winter rains and minimum storage occurring in October just before winter rains begin. The ambient precipitation lysimeters had the smaller seasonal amplitude compared with the irrigated lysimeters. The vegetated lysimeters had the smaller storage having minimum values near 90 mm in ambient or irrigated lysimeters. The non-vegetated lysimeters had the larger storage, which was over 200 mm over the entire period. The only period where drainage occurred was in the non-vegetated irrigated lysi-

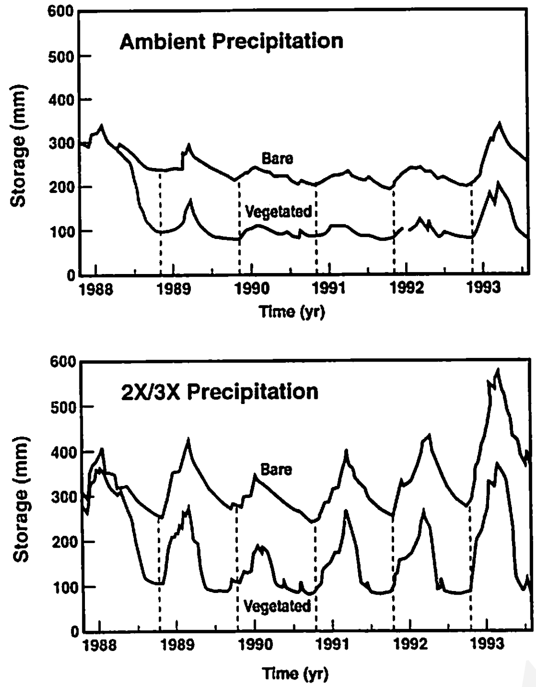

Fig. 5. Water storage for weighing lysimeters.

meter in 1993 when storage exceeded the 500-mm level needed to cause drainage.

Vegetation plus soil evaporation is able to return at least 480 mm yr^{-1} to the atmosphere. Water storage in the vegetated lysimeters is reduced to a unique lower limit every year, which indicates that the plants use all the water available to them. Plant biomass in the irrigated lysimeters was more than twice as great as biomass in the ambient precipitation lysimeters, which indicates that water is limiting for biomass production even with twice ambient precipitation.[14] A capillary break system with vegetation verifies the performance of capillary barriers for the Hanford Site even under extreme conditions.

The non-vegetated lysimeters always had more water stored in them than the vegetated lysimeters. In only one instance did drainage occur in the non-vegetated lysimeters. This occurred in the 3 times ambient precipitation treatment when the drainage limit was exceeded in February 1993. This indicates that a capillary barrier will prevent drainage under almost all worst-case scenarios for the barrier. The worst case scenario is a fire that destroys

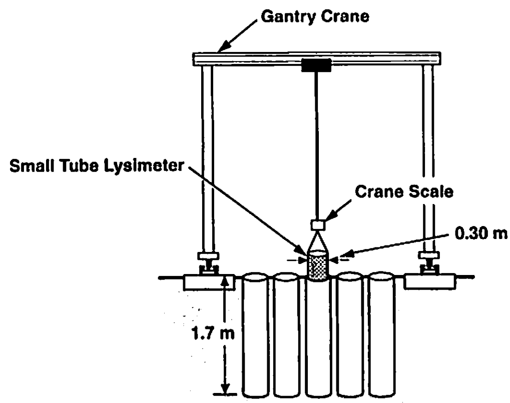

Fig. 6. Small tube weighing lysimeters at the 200 Area Lysimeter Facility.

all vegetation with virtually no recovery followed by an extremely wet winter (*e.g.*, more than 3 times ambient precipitation). This scenario is not very likely because vegetation usually recovers rapidly after fire in the shrub-steppe.[20] Thus, it is reasonable to conclude for the Hanford Site, that vegetated capillary barriers, similar the lysimeter design, will not allow drainage under present or enhanced precipitation regimes.[14]

The study of the effect of surface conditions on soil water storage was also done at the 200 Area Lysimeter Facility (Fig. 1) in small tube weighing lysimeters (Fig. 6). Soil water storage will be minimized if a surface gravel layer is not used and if plants are used to transpire water back into the atmosphere. We hypothesized that a gravel layer on the surface would eventually result in drainage through the capillary break, and that plants would minimize soil water storage. Because the environment where the barrier is to be built has high winds that could cause loss of fine surface soils, we observed the effect that an admixed surface (gravel mixed into the fine soil) would have on water budgets. Admixes lead to a surface armor development that reduces wind erosion.[21] Finally, because of high winds, it was hypothesized that dune formation or a sand on top of the barrier would increase soil water storage.

The purpose of this study was to determine the optimum surface condition to minimize the potential for drainage. We tested the effect of soil, admix, sand, and gravel surfaces with and without vegetation on soil water budgets and drainage. We also added water (2 and 3 times annual precipitation) to the system to determine how much water these treatments could hold before drainage occurred.

The small-tube lysimeter facility consists of an array of 21 rows of 5 lysimeters (Fig. 6). The lysimeters are 170 cm long by 30 cm wide sections of plastic pipe. The bottom ends are fitted with a cap and a drain port. The lysimeters are placed in larger plastic pipe sleeves. Weighing is done with a calibrated load cell attached to the gantry. Weighing and drainage measurements were taken monthly from December 1988 through August 1992. The lysimeters were filled with Warden silt loam overlying a capillary break consisting of sand on top of gravel. The surface treatments consisted of soil, an admix of gravel (30% by weight) in the top 20 cm of soil, gravel, and sand. These treatments were tested with and without vegetation and with and without additional water.

Since the beginning of the experiment under ambient precipitation conditions, all the soil and admix lysimeters have had a net decrease in soil water storage. Vegetation caused a greater decrease in storage than in non-vegetated lysimeters. Enhanced precipitation resulted in a small increase in storage in the non-vegetated lysimeters. Enhanced precipitation with vegetation still resulted in a decrease in storage over time. This is because of the associated increase in vegetation associated with additional water.

The presence of gravel or sand on top of the soil column has resulted in increased storage and drainage whether the lysimeters were irrigated or not. The presence of vegetation prevented drainage from occurring in the non-irrigated gravel mulch lysimeters. The addition of water to the gravel and sand surface lysimeters resulted in drainage whether they were vegetated or not.[1, 22]

On the basis of on these results, we conclude that an admix surface with vegetation would minimize the chance of drainage and erosion.

2) Plants

Vegetation plays a significant role in the achievement of a successful barrier in arid environments.[4] Plants control soil water storage and dynamics, protect the surface from wind and water erosion, and can potentially compromise the barrier by extending roots into the waste. Work on these issues will be reviewed leading to recommendations for the type of vegetation that should be established on the prototype barrier to minimize the chances of recharge, erosion, and root intrusion into the buried waste.

It has been established at Hanford that areas dominated by shallow-rooted annuals such as *B. tectorum*[23] can accumulate water beneath the root zone which can, potentially, lead to recharge.[24] Variation in the rooting depth of deep rooted perennials is associated with variation in soil water storage.[20] Soil water storage increased below the 125 cm depth in a *Pseudoroegneria spicata* dominated community in comparison with a more deeply rooted community dominated by *A. tridentata* and *P. spicata*. The presence of deeply (200 cm) rooted shrubs such as *A. tridentata* and *Grayia spinosa* at McGee Ranch has been demonstrated to extract more water from the soil profile than areas dominated by sparse vegetation. Areas dominated by these shrubs were also able to extract two times normal precipitation from the soil profile.[18] We recommend that deep-rooted perennials be established on the barrier to minimize chances that recharge will occur.

The establishment of deep-rooted plants on the surface of the barrier brings up the issue of roots entering the waste zone. Deep-rooted plants (*Chrysothamnus nauseosus*;[25] *Salsola kali*[26]) have been observed to accumulate fission products when growing over buried radioactive wastes. The presence of fission products in the shoot is a consequence of roots penetrating the radioactive wastes. Past workers have sought to prevent the intrusion of roots into buried wastes by maintaining a loose rock layer between the waste and the surface soils.[10] They were successful as long as an asphalt layer was present to prevent soils, and thus roots, from filling cracks in the rock layer. Others have prevented roots from entering wastes by keeping the surface barren of plants. This has been done by placing gravel on the surface and maintaining an herbicide program.

This practice, unfortunately, leads to drainage because of the presence of the gravel and the lack of plants.[4, 27]

On the prototype barrier, the chances that roots will enter buried wastes are small because there will be a loose rock layer between the waste and the surface soils. As long as this zone is dry, roots will not enter. Even if this zone should become wetted, the asphalt layer below it should prevent roots from enter the waste below the asphalt.

3) Animals

Animal studies have addressed the impact of large and small mammal burrows on soil moisture dynamics. It was hypothesized that burrows would increase the accumulation of water by allowing water to drain into the holes. In addition, there was concern that burrows could provide a preferential pathway for water to bypass the fine-soil layer, enter the coarse layer, and eventually, enter the waste.[19] These studies were done in natural systems[28] and in large steel boxes buried at grade.[29] Supplemental rain was added to test the impact of higher rainfall on potential drainage. Measurements were taken using calibrated neutron probes down to a depth of 125 cm. The main result was that small animal burrows had no significant effect on soil water storage, and that large animal burrows had only a small effect in winter that disappeared in spring or summer. The addition of twice normal precipitation did not result in increased soil water storage. An explanation for these results is that evaporation was enhanced by a combination of soil turnover and subsequent drying and by ventilation into the soil column through the burrows. Although animals apparently do not significantly influence soil water budgets they still pose risks associated with uptake of wastes, wind erosion of soils brought to the surface, and plant community dynamics.[30]

The risk of animals intruding through the barrier structure is considered small given that intrusion into buried waste could be prevented if a layer of loose rock covered with an asphalt emulsion was placed between the buried waste and the topsoil.[10] The proposed permanent isolation barrier has a thick asphalt layer below 3 m of a layered structure of fine soil, sand, gravel, and riprap rock of coarse gravel (Fig. 2). The rock and asphalt should physically prevent intrusion and the 3 m depth of the cover is too deep for most animal burrow depths. Burrow depths are less than 1.5 m for a wide variety of potential animals.[30]

The potential for the loss of cast soil from burrows by wind erosion that could eventually lead to loss of the silt layer, which could compromise the barrier, has not been measured. The impact of animal burrow soil disturbance on plant community dynamics has not been carefully examined. It has been observed that weedy annuals established on soils disturbed by animals.[28] Disturbed soils potentially lead to a plant community dominated by weedy annuals that, if shallow rooted, could increase the potential for drainage.

4) Prototype Barrier

The Hanford permanent isolation barrier program has investigated how various subcomponents and processes interact under worst-case environmental conditions to assess the validity of our concepts for the long-term isolation of wastes from environmental dispersion. Some of these subcomponents are listed in Table 1. A complete review of progress has been documented.[16] Although we have gained significant experience on how subcomponents respond to stressful conditions, we still need to understand how a barrier behaves as an integrated unit. In addition, construction issues have not been addressed. To investigate how well our construction concepts reflect true operating conditions and test how an integrated barrier responds to stress, we have initiated construction of a prototype barrier.[9]

The barrier will be constructed on the 200 Area Plateau at the 200 BP-1 Operable Unit. It will be built over the B-57 Crib located in the northwest quadrant of the 200 East Area (Fig. 1). The surface area of the entire barrier will be about 2 hectares. The surface will be elevated with one side relatively steep (2 : 1 horizontal to vertical) covered with basalt rip-rap. The other side will be shallow (10 : 1) and will consist of local gravel/sand backfill. The test area of the barrier will be 2,700 m^2.

The prototype surface will be sectioned into four study plots, two of which will receive water at 3 times ambient precipitation. The surface will be vegetated with a combination of deep-rooted shrubs and grasses. Water balance monitoring will be taken in vertical and horizontal access ports with neutron probes. Drainage measurements will be made with pan-type lysimeters under each plot. Drainage along the slopes will also be monitored.

Wind erosion testing will include documenting the wind profile of the prototype and evaluating wind erosion from the sides and top surfaces of the test plots, using standard erosion pin techniques. Water erosion will also be documented for each plot, and the erosion potential of the steep side slopes carefully assessed, particularly after the water application tests. Biointrusion testing will be confined primarily to observation of root penetration into soil and sublayers using mini-rhizotron systems, which allow for root observations during and after plant establishment.

The effectiveness of an asphalt sublayer to shed water will be investigated. This layer, placed beneath the entire barrier, will be designed to perform as a low-permeability barrier, diverting the water that infiltrates the barrier on the sideslopes. This diverted water will be captured at the toe of the barrier slope and will be used by riparian vegetation growing at the toe of the slope. It is intended that all water incident upon the barrier will cycle back into the atmosphere through evapotranspiration. Assessment of how well this process works will be an important feature of prototype testing and monitoring.[9]

4. Summary

Progress in the Hanford Site Surface Barrier Development Program has been reviewed concerning the ability of engineered barriers to isolate buried wastes from environmental dispersion. A fine-soil surface with a relatively high infiltration rate is planned to limit infiltration below the fine soil by inducing temporary storage near the surface. Transpiration by vegetation and evaporation will return stored water to the atmosphere. A capillary break created by the interface of the fine-soil layer and coarser textured material below will further limit infiltration and promote evapotranspiration. Should water pass the interface, it will drain laterally on a low permeability asphalt layer through a coarse- textured sand/gravel filter layer.

Current work will integrate our scientific and engineering concepts on a large prototype barrier to determine if it can isolate buried wastes from environmental dispersion. This effort promises to provide an economically and environmentally sound solution to the waste problem at the Hanford Site.

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Effective Porosity, Longitudinal Dispersivity and Hydraulic Conductivity of a Sedimentary Formation by Laboratory Tracer Tests and Field Tracer Tests

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Abstract

Field tracer tests in a Tertiary sedimentary rock and laboratory tracer tests using core samples of the sedimentary rock and bentonite and quartz sand mixtures. The result indicates that test scale should be considered to evaluate effective porosity and longitudinal dispersivity. As the test scale increases, effective porosity decreases and longitudinal dispersivity increases. The following empirical relationship has been found for the sedimentary formation: longitudinal dispersivity equals one tenth of test scale. This is in agreement with the relationship presented in the paper by LEONHART *et al.*[1] From the laboratory scale to the field scale, the decrease in effective porosity and increase in hyudraulic conductivity is due to the existence of cracks or fissures. At the laboratory scale, the decrease in effective porosity is probably due to a loss of connectivity of continuous pores.

1. Introduction

A lot of groundwater pumped up through deep boreholes and wells was used for desert development in desert nations. Planned or controlled pumping of groundwater is necessary because the water table goes down and the water content of the aquifer decreases around the boreholes or wells and springs and other wells which used for same aquifer are dried up. It is necessary for the planning or controlling of pumping to clear groundwater flow. In this paper, permeability, dispersion coefficient and effective porosity, which were necessary for estimation of groundwater-flow, were analyzed by tracer tests. Especially, a design for the underground dam needs effective porosity which is used for an estimation of storage volume.

Porosity is defined as the total pore proportion of a rock or soil sample and includes closed pores, branches and continuous pores. Effective porosity is defined as the proportion of pores through which water flows and consists of continuous pores only. Therefore, in most cases, porosity is larger than effective porosity.[2] Effective porosity should be determined in order to calculate the actual velocity of groundwater, but porosity is sometimes used as effective porosity due to the difficulty involved in measuring effective porosity. As the actual velocity of groundwater is an essential parameter for the estimation of mass trransport in groundwater, accurate estimation of effective porosity is particularly important.

Dispersion is also an essential phenomenon for estimating mass transport in groundwater. In this study, longitudinal dispersivity is used as the parameter which represents dispersion. Longitudinal dispersivity is defined as the dispersion coefficient divided by actual velocity.

We will discuss effective porosity and longitudinal dispersivity as estimated by laboratory tracer tests and field tracer tests. For this paper, a field tracer test and laboratory tracer tests using core samples were performed on a Neogene sedimentary rock in the Toki area. In the Matsumoto area, a field tracer test alone was performed on a Miocene sedimentary rock. We can compare values of effective porosity and longitudinal dispersivity from the laboratory tests with those from the field tracer test and study the effect of test scale on these two parameters. In the laboratory tests no cracks appeared in the samples because latent cracks

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in the core sample separated during boring. However selective flow paths, such as cracks, may have existed during the field tests. Therefore, we performed laboratory tracer tests using bentonite and sand mixtures with the same conditions of porosity but different pore geometry in order to estimate the influence of selective flow paths on hydraulic conductivity, effective porosity and dispersion.

Conservative tracers were suitable for the tracer test which was carried out to estimate effective porosity and longitudinal dispersivity, as it was not necessary to consider adsorption of tracers into the rocks and soil. We selected Br^- and Cl^- as tracers, and performed batch experiments to confirm that Br^-

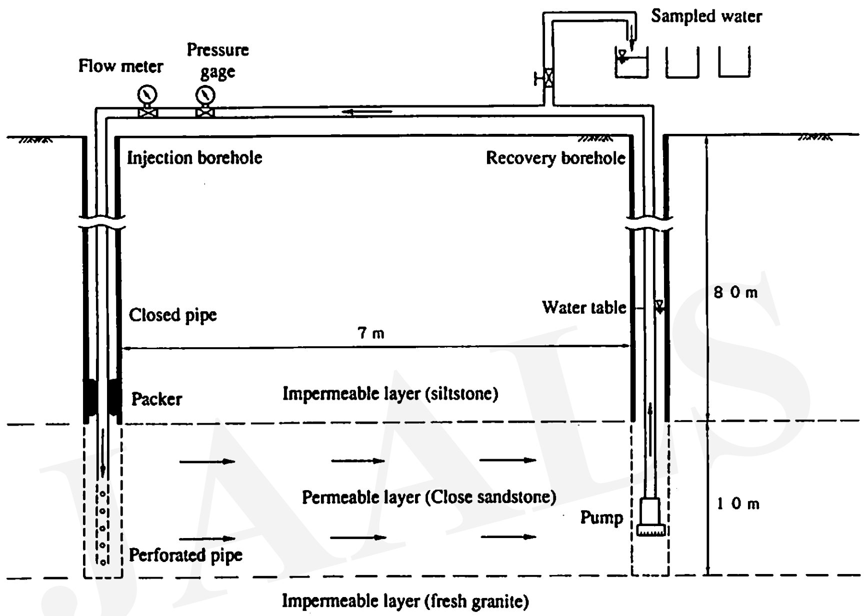
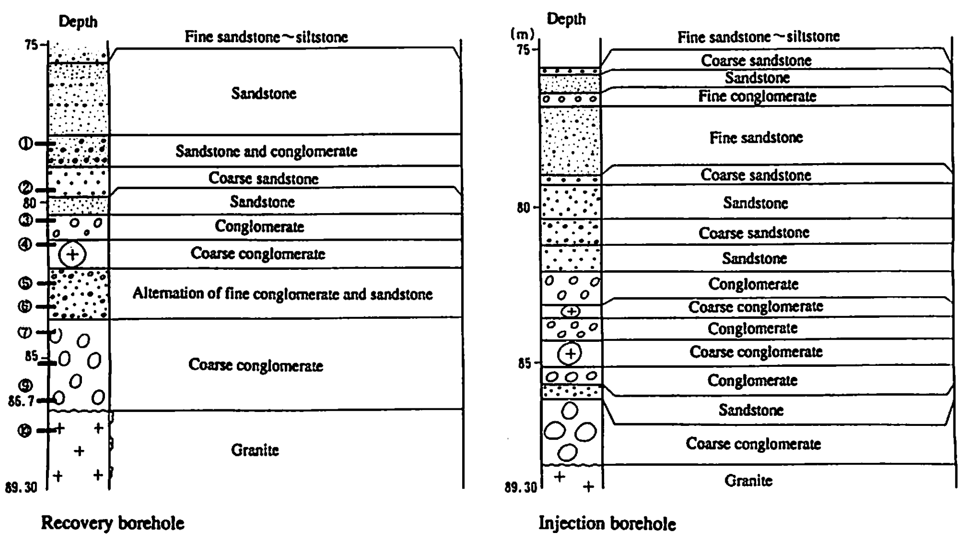


Fig. 1. Schematic figure of the Toki field tracer test.



①~⑩ sampled core position for

Fig. 2. Geological column of the boreholes at the Toki site.

and Cl^- would not be adsorbed by the core samples of the sedimentary rock or the bentonite and quartz sand mixtures. The results suggested that Br^- and Cl^- could be regarded as conservative tracers in the tracer tests.

2. Toki Field Tracer Test

The field test site was located in the southern part of Gifu prefecture, central Japan. In this area, several kinds of sedimentary rocks unconformably cover granite bed rock. There was a permeable zone composed of Neogene coarse sandstone and weathered granite above the unconformity.[3]

1) Method

Figure 1 shows a schematic figure of the field tracer test. There were two boreholes 7 m apart and each about 90 m in depth. Figure 2 shows geological columns at the boreholes. A permeable layer consisting mainly of weathered granite and coarse sandstone, which was formed in the Neogene period, existed from 80 to 90 m in depth. This layer was sandwiched between impermeable layers of siltstone above and fresh granite below. The boreholes were fully lined from 0 to 80 m in depth and perforated in the zone of permeable coarse sandstone. Before the tracer solution was injected, groundwater was pumped out at the recovery borehole and reinjected at the injection borehole.

Groundwater was circulated until a steady-state groundwater flow was obtained. At this point the circulation flow rate was maintained at 7,800 $cm^3\ min^{-1}$ and Br^- tracer solution was injected at the injection borehole. The original volume of tracer solution which contained 2 kg NaBr was 180,000 cm^3. Br^- was selected because of its low background concentration in the groundwater. During the test, groundwater was sampled regularly at the recovery borehole to measure the concentration of Br^- by ion exchange chromatography.

2) Gelhar method

In this analysis we used the Gelhar method and numerical analysis and compared the results. From the breakthrough curve for Br^- in the field tracer test, effective porosity and longitudinal dispersivity were calculated based on the following analytical solution of the two dimensional dispersion equation for a two-well (pumping-injection) flow system:[4]

$$C_w = \frac{M}{Q}\int_{\Phi=0}^{1} \frac{Q\exp[-(a-T)^2/4eb]}{\varepsilon h L^2 (4\pi e b)^{1/2}}\, d\Phi$$

$$T = \frac{Qt}{\varepsilon h L^2} \qquad e = \frac{\alpha}{L}$$

$$a(\beta) = \frac{\pi(\sin\beta - \beta\cos\beta)}{\sin^3\beta};\ \beta = \pi\varphi$$

$$b(\gamma,\beta) = \pi^2 \frac{\left[\frac{(\gamma+\beta)}{2} + \frac{(\sin\gamma\cos\gamma)}{2} + \frac{(\sin\beta\cos\beta)}{2} - 2\cos\beta(\sin\gamma+\sin\beta) + (\gamma+\beta)\cos^2\beta\right]}{2\sin^5\beta} \quad (1)$$

where

C_w: concentration at recovery borehole, t: time, ε: effective porosity, Q: flow rate, h: thickness of permeable layer, M: mass of tracer, γ: displacement of the tracer pulse, φ: stream function; $\Phi = 2h\varphi/Q$, L: distance between boreholes, and α: longitudinal dispersivity.

Table 1 shows the system parameters used in the analysis of the field tracer test. Figure 3 shows the correlation between the concentration of Br^- at the recovery borehole and the time elapsed from the start of tracer injection. The analytical solution of the dispersion equation for the two well pumping system found effective porosity and longitudinal dispersivity to equal 4.5% and 3.5 m.

3) FEM analysis

Initially, the velocity distribution of the flow field and layer permeability were analyzed as a seepage problem using finite element method (FEM). Next, the advection-dispersion equation was used to numerically analyze the tracer test results.

(1) Seepage analysis

The equation governing steady-state groundwater flow in a horizontal two-dimensional system is generally given as,

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} = 0 \quad (2)$$

where

ϕ: piezometric head, x, y: Cartesian coordinates

The system boundaries are impermeable excepting the injection and recovery boreholes.

Table 1. Parameters used in the two dimensional analysis of the Toki field tracer test.

Distance (m)	7
Flow rate ($cm^3 min^{-1}$)	7,800
Thickness of permeable layer (m)	10
Mass of tracer (g)	1,920 (Br^-)
Effective porosity (%)	2–30
Longitudinal dispersivity (m)	0.014–7

Boundary conditions can be given as follows;

$\phi=\phi_0$ at the recovery borehole

$Q=Q_0$ at the injection borehole (3)

ϕ_0: steady-state piezometric head level (−15 m from natural water table)

Q: flow rate

Q_0: constant flow rate (3,900 $cm^3 min^{-1}$)

A seepage analysis was performed using FEM on equation (2). The analysis was simplified using the boundary conditions described by equation (3).

Figure 4 displays an analytical model for the seepage analysis of half of the horizontal section of the analytical region. The circulation

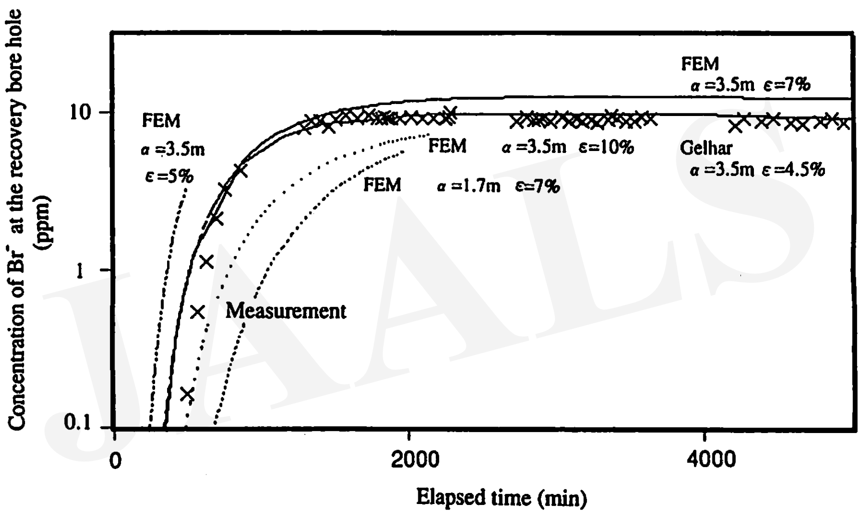


Fig. 3. Relationship between elapsed time after the start of tracer injection and concentration of Br^- at the recovery borehole at the Toki site.

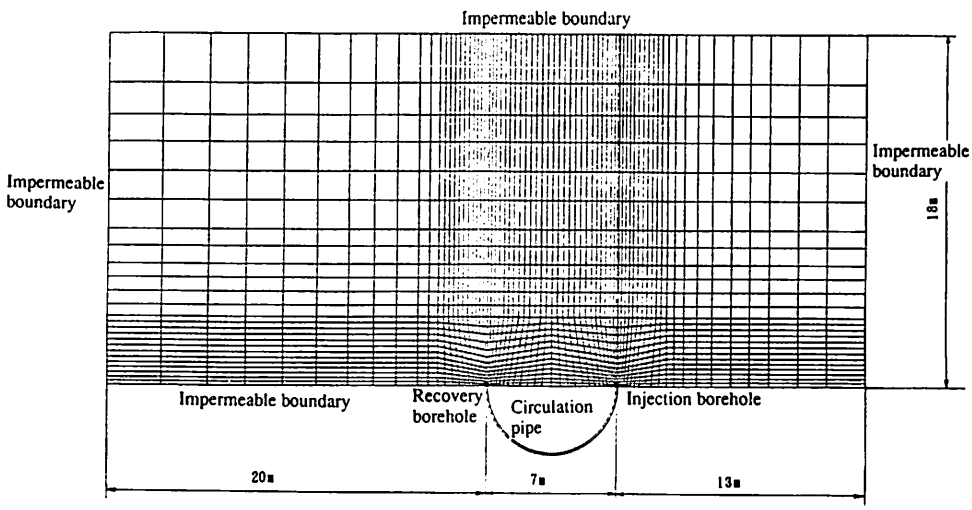


Fig. 4. Analytical model (horizontal section) at the Toki site.

pipe connecting the pumping injection boreholes was not included in the analysis. Table 2 shows the parameters and boundary conditions used in the seepage analysis.

Figure 5 shows the distribution of analyzed piezometric-head values. When hydraulic conductivity of the layer becomes 2×10^{-6} cm sec^{-1}, the analyzed piezometric head at the injection borehole agrees with the head calculated from the observed injection pressure.

(2) Migration analysis

A coupled equation governing groundwater flow and advection-dispersion in a horizontal two-dimensional system is given as follows,

$$\frac{\partial C}{\partial t}=D\frac{\partial^2 C}{\partial x^2}+D\frac{\partial^2 C}{\partial y^2}-Vx\frac{\partial C}{\partial x}-Vy\frac{\partial C}{\partial y} \quad (4)$$

$$Vx=vx/\varepsilon,\ Vy/\varepsilon$$

where

ε: effective porosity, C: concentration, D: dispersion coefficient, Vx, Vy: actual velocity in the x and y directions, and vx, vy: apparent velocity in the x and y directions.

Table 2. Parameters and boundary conditions used in the seepage analysis at the Toki field tracer test.

Thickness of permeable layer	10 m
Hydraulic conductivity	5×10^{-6}–1×10^{-4} cm/sec
Boundary conditions	Impermeable boundary (Except the boreholes)
Injection borehole	Constant flow rate: 3,900 cm^3/min (half area)
Recovery borehole	Steady-state piezometric head level (−15 m from natural water table)

Two different dispersion coefficients are given as follows,

$$D1=\alpha|V|+Dm,\ D2=Dm$$

where

$D1$: dispersion coefficient parallel to groundwater flow direction, $D2$: dispersion coefficient perpendicular to groundwater flow direction, $|V|$: $\sqrt{Vx^2+Vy^2}$, α: longitudinal dispersivity, and Dm: molecular diffusion coefficient (2.8×10^{-9} cm^2 sec^{-1}).

Using $D1$ and $D2$, tensor Dij is given as follows,

$$\begin{bmatrix} D_{xx} & D_{xy} \\ D_{yx} & D_{yy} \end{bmatrix}=\begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} D_1 & 0 \\ 0 & D_2 \end{bmatrix}\times\begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$$
$$=\begin{bmatrix} D_1\cos^2\theta+D_2\sin^2\theta & D_1\sin\theta\cos\theta-D_2\sin\theta\cos\theta \\ D_1\sin\theta\cos\theta-D_2\sin\theta\cos\theta & D_1\sin^2\theta+D_2\cos^2\theta \end{bmatrix} \quad (5)$$

where $\theta=\arctan(Vx/Vy)$

Using equation (5), eqauation (4) becomes:

$$\frac{\partial C}{\partial t}=D_{xx}\frac{\partial^2 C}{\partial x^2}+D_{xy}\frac{\partial^2 C}{\partial x\partial y}+D_{yx}\frac{\partial^2 C}{\partial y\partial x}+D_{yy}\frac{\partial^2 C}{\partial y^2}-V_x\frac{\partial C}{\partial x}-V_y\frac{\partial C}{\partial y} \quad (6)$$

This is a two-dimensional advection-dispersion equation. The dispersion coefficient depends on actual velocity and is anisotropic. The system boundaries are impermeable except at the injection and recovery boreholes.

$$C=C_0 \text{ at the injection borehole}$$
$$F=F_0 \text{ at the recovery borehole} \quad (7)$$

where

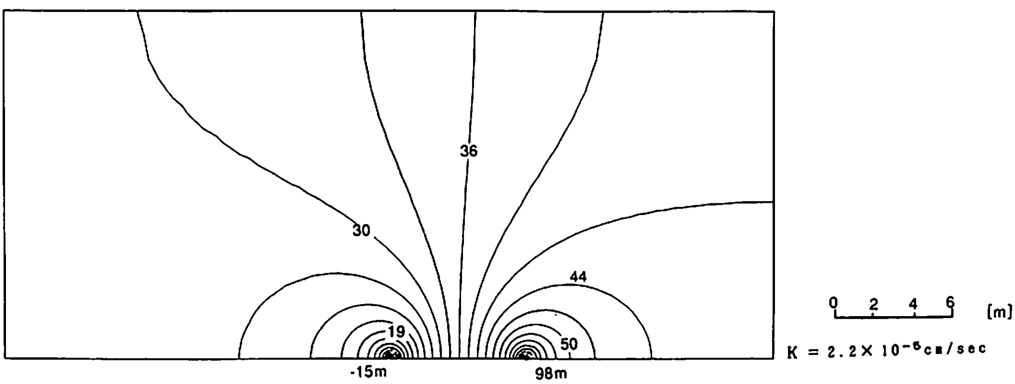


Fig. 5. Analyzed piezometric-head distribution at the Toki site (horizontal section).

C_0 : initial cocentration at the injection borehole, F: flux of mass ($\partial C/\partial t$), and F_0: steady state flux of mass at the recovery hole.

A migration analysis was performed using FEM and the boundary conditions described by equation (7). The computer code used was developed by Utsugida.[5)]

Figure 4 shows an analytical model for the migration analysis of half of the horizontal section of the analytical region including the circulation pipe. The flow velocity through the circulation pipe was 0.065 cm sec^{-1} (3,900 cm^3 min^{-1}÷10 cm (width)÷1,000 cm (height)= 0.39 cm min^{-1}). Table 3 displays the parameters and boundary conditions used in the migration analysis.

Before the 180,000 cm^3 tracer solution containing 8,300 ppm Br^- (NaBr: 2 kg) was injected at the injection borehole, there were 700,000 cm^3 of water in the injection borehole. Therefore we assumed that the tracer concentration was 1,700 ppm (180,000 cm^3×8,300 ppm÷(700,000+180,000)cm^3) and the injection time was 112.8 min ((700,000+180,000) cm^3÷7,800 cm^3 min^{-1}).

Table 3. Parameters and boundary conditions used in the migration analysis at the Toki field tracer test.

Initial concentration	1,700 ppm (112.8 min)
Hydraulic conductivity	2.2×10^{-5} cm/sec
Flow velocity distribution	Seepage analysis used
Effective porosity	Maximum 30%
Longitudinal dispersivity	0.014–7.0 m
Thickness of permeable layer	10 m
Boundary condition	Impermeable

(3) Numerical results

Figure 3 shows the correlation between the concentration of Br^- at the recovery borehole and the time elapsed from the start of tracer injection. The relationship was obtained from the two-dimensional FEM migration analysis. Effective porosity and longitudinal dispersivity were determined to be 7% and 3.5 m respectively. The analytical solution of the dispersion equation for the two well pumping system found effective porosity and longitudinal dispersivity to equal 4.5% and 3.5 m. The difference between the 4.5 and 7% effective porosity values is thought to relate to the difference between the initial tracer-concentration values used by the two methods.

Figures 6, 7 and 8 show the analyzed Br^- concentration distributions by FEM using 3.5 m longitudinal dispersivity and 7% effective porosity, 2, 36 and 100 hours after the start of tracer injection. Figure 6 indicates concentric spreading of Br^- at the beginning of tracer

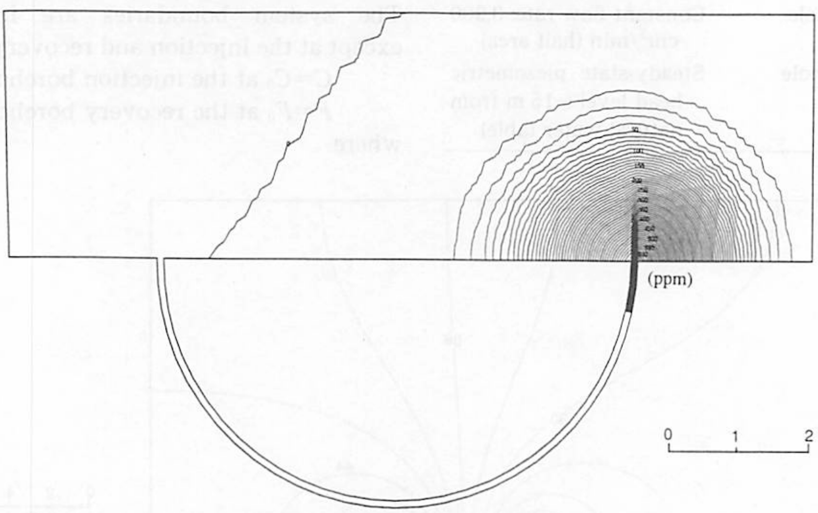


Fig. 6. Analyzed Br^- concentration distribution 2 hours after the start of tracer injection at the Toki site (horizontal section).
α=3.5 m ε=7%

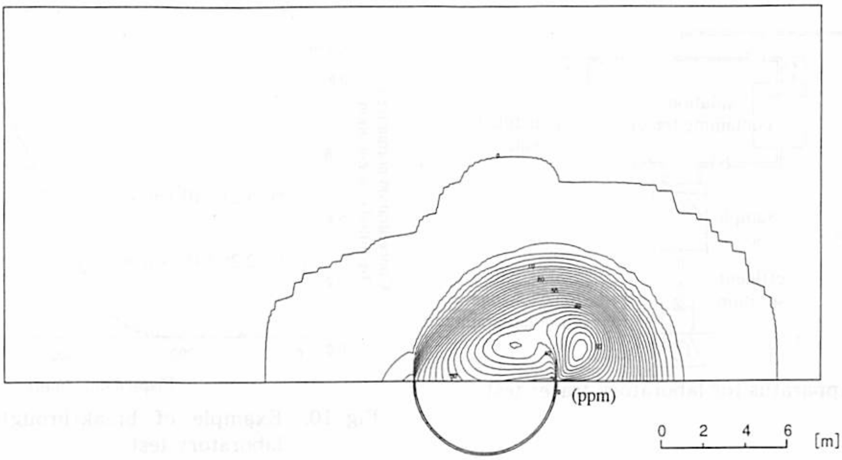


Fig. 7. Analyzed Br^- concentration distribution 36 hours after the start of tracer injection at the Toki site (horizontal section).
α=3.5 m ε=7%

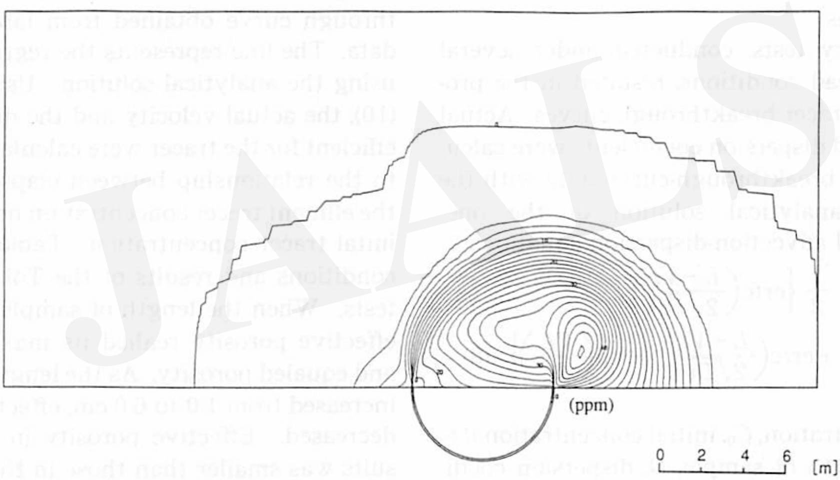


Fig. 8. Analyzed Br^- concentration distribution 100 hours after the start of tracer injection at the Toki site (horizontal section).
α=3.5 m ε=7%

injection. Figures 7 and 8 indicate the presence of two Br^- concentration peaks around the injection borehole and these concentration peaks reduce in progression.

3. Toki Rock Sample Laboratory Tracer Tests

1) Method

Porosities of the core samples taken from the permeable layer were determined by weighing the samples in both water saturated and dry condition. The porosity values ranged from 6～47% and were mainly concentrated in the range of 25～30%.[6] Three samples of different porosities were used in laboratory tracer tests. Figure 9 shows the laboratory test apparatus. To determine effective porosity, tracer solutions containing 100 to 300 ppm Br^- or Cl^- were pumped into the column under constant flow rates. Flow rate were maintained at a constant level through the manual adjustments of the nitrogen cylinder valve. The volume of effluent solution was measured to determine the flow rate. The tracer concentration of the effluent solution was analyzed using

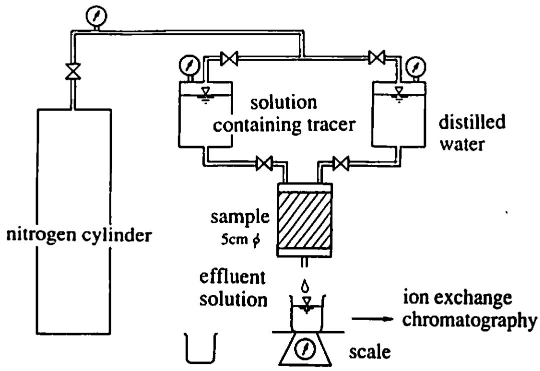


Fig. 9. Apparatus for laboratory tracer test.

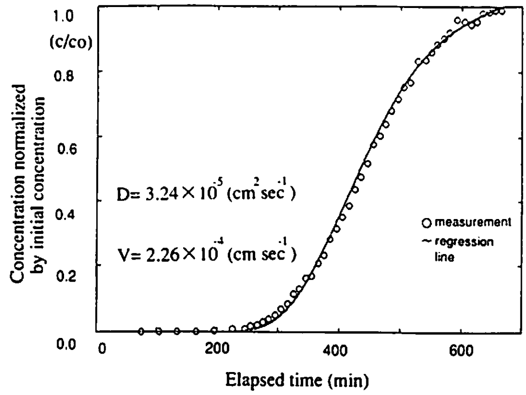


Fig. 10. Example of breakthrough curve in laboratory test.

ion exchange chromatography.

2) Analysis

Laboratory tests, conducted under several constant head conditions, resulted in the production of tracer breakthrough curves. Actual velocity and dispersion coefficients were calculated using breakthrough-curve data with the following analytical solution of the one-dimensional advection-dispersion equation:.

$$\frac{C}{C_0}=\frac{1}{2}\left\{\mathrm{erfc}\left(\frac{L-Vt}{2\sqrt{Dt}}\right)+\mathrm{erfc}\left(\frac{L+Vt}{2\sqrt{Dt}}\right)\times\exp\left(\frac{VL}{D}\right)\right\} \quad (8)$$

where

C: concentration, C_0: initial concentration ($t=0$), L: length of sample, D: dispersion coefficient, t: time, and V: actual velocity.

The initial and boundary conditions are given as;

C_0=constant, V=constant

$C=0$, $X=\infty$, at all times

$C=0$, $X>0$, at $t=0$.

From the actual velocity (V) and the monitored constant flow rate (Q), the cross-sectional area of void through which the pore water passed (A) was calculated by the equation $A=Q\ V^{-1}$. The effective porosity (ε) was then calculated, using the equation $\varepsilon=A\ A'^{-1}$ based on the Depuit-Forchheimer assumption. A' represents the total area of the sample cross section.

3) Results

Figure 10 shows an example of a breakthrough curve obtained from laboratory test data. The line represents the regression curve using the analytical solution. Using equation (10), the actual velocity and the dispersion coefficient for the tracer were calculated accoring to the relationship between elapsed time and the effluent tracer concentration normalized by inital tracer concentration. Table 4 gives the conditions and results of the Toki laboratory tests. When the length of sample was 1.0 cm, effective porosity reahed its maximum value and equaled porosity. As the length of samples increased from 1.0 to 6.0 cm, effective porosity decreased. Effective porosity in the field results was smaller than those in the laboratory results. Hydraulic conductivity (2×10^{-5} cm sec^{-1}) in the field results was larger than those ($2\times10^{-8}-4\times10^{-7}$ cm sec^{-1}) in the laboratory results.

4. Matsumoto Field Tracer Test

1) Method

Figure 11 shows the sectional plan of the field tracer test. Matsumoto tunnel was under construction at the plateau which consisted mainly of Tertiary volcanic sediments formed in the Miocene period in the north of Matsumoto city, central Japan. The altitude at the borehole bottom and the tunnel was the same. At this point, it was 331 m between the borehole and the cutting face at the east side of the

Table 4. Conditions and results of laboratory tests at the Toki site.

Rock Type	Porosity (%)	Hydraulic conductivity (cm sec^{-1})	Length of sample (cm)	Actual velocity (cm sec^{-1})	Flow rate (cm^3 sec^{-1})	Dispersion coefficient (cm^2 sec^{-1})	Effective porosity (%)
Sandstone	27	2.6×10^{-7}	1.10	5.2×10^{-4}	1.9×10^{-3}	9.2×10^{-5}	24
				1.4×10^{-4}	5.5×10^{-4}	3.5×10^{-5}	27
				2.9×10^{-4}	1.2×10^{-3}	8.5×10^{-5}	28
		4.2×10^{-7}	2.01	9.5×10^{-4}	3.2×10^{-3}	2.5×10^{-4}	22
				1.2×10^{-4}	4.6×10^{-4}	3.8×10^{-5}	24
				2.0×10^{-3}	7.4×10^{-3}	9.4×10^{-4}	25
	31	2.4×10^{-8}	1.99	2.9×10^{-4}	1.1×10^{-3}	4.5×10^{-5}	25
				6.5×10^{-5}	2.6×10^{-4}	8.8×10^{-6}	26
				1.7×10^{-4}	7.1×10^{-4}	2.3×10^{-5}	27
				3.7×10^{-4}	1.5×10^{-3}	3.8×10^{-5}	27
				6.8×10^{-5}	2.8×10^{-4}	8.2×10^{-6}	27
		3.1×10^{-8}	5.01	8.5×10^{-5}	2.7×10^{-4}	1.4×10^{-5}	21
				4.5×10^{-5}	1.5×10^{-4}	7.6×10^{-6}	21
				2.2×10^{-4}	7.3×10^{-4}	3.5×10^{-5}	22
				2.0×10^{-4}	6.8×10^{-4}	2.7×10^{-5}	23
				1.7×10^{-4}	6.1×10^{-4}	2.5×10^{-5}	24
		4.7×10^{-8}	6.05	4.3×10^{-4}	1.4×10^{-3}	6.9×10^{-5}	22
				2.3×10^{-4}	8.1×10^{-4}	3.2×10^{-5}	24
	29	8.3×10^{-8}	2.37	5.5×10^{-4}	1.7×17^{-3}	2.3×10^{-4}	21
		4.2×10^{-8}	6.14	3.4×10^{-4}	9.8×10^{-4}	7.5×10^{-5}	19

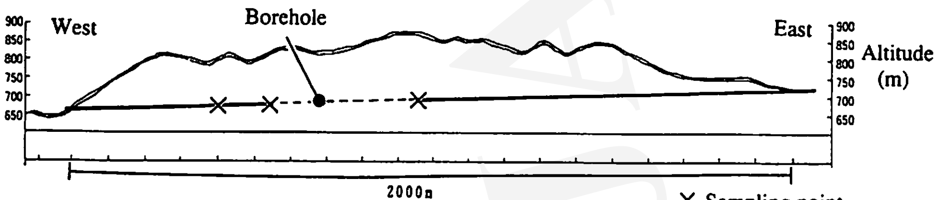


Fig. 11. Sectional plan at the Matsumoto field tracer test.

tunnel and 130 m between the borehole and the cutting face at the west side of the tunnel. The tracer solution was injected at the borehole for 30 minutes and groundwater was sampled in the tunnel for 30 days. The original volume of tracer solution which contained 30 kg NaBr was 80,000 cm^3. Br^- was selected because of its low background concentration in the groundwater. During the test, seepage water along the tunnel was sampled regularly to measure the concentration of Br^- by ion exchange chromatography. There were 3 sampling points (130 and 265 m from the borehole at the west side of the tunnel and 331 m from the borehole at the east side of the tunnel).[7] The tracer concentrations at 265 and 331 m apart from the borehole were very low under the detection limit. For the past 2 years the groundwater level has gone down. But the groundwater level at the borehole was constant before and after the tracer solution injection.

2) **Analysis**

We used three-dimensional groundwater flow and an advection-dispersion code using

FEM (MIGR3D) made by Kawamura.[8] This code can't be applied for unsaturated zones. It is necessary to determine a position of groundwater level which is a boundary between a saturated zone and an unsaturated zone for using this code. Therefore, we estimated the position of groundwater level by seepage analysis using FEM.[8] Using migration analysis, groundwater levels were coincided with the upper surface of three dimensional analytical model and MIGR3D was applied for this field tracer test results. We couldn't find any change in groundwater levels using the borehole, wells and springs during the test. Probably the period of the test was shorter than the tunnel construction period. During the test, the change of groundwater levels was thought to become smaller. In this analysis, we assumed that the groundwater flow was steady-state and the piezometric heads were constant. Figure 12 shows the seepage and migration analysis areas.

(1) Seepage analysis

The equation governing steady-state groundwater flow in a three-dimensional system is generally given as,

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = 0 \qquad (9)$$

where

ϕ: piezometric head, x, y, z: cartesian coordinates.

The system boundaries are impermeable excepting the tunnel and springs. Boundary conditions can be given as follows;

$$\phi = \phi_0 \text{ at the the tunnel and springs} \qquad (10)$$

ϕ_0: steady-state piezometric head level

A seepage analysis was performed using FEM on equation (9). The analysis was simplified using the boundary conditions described by equation (10).

Table 5 shows the parameters and boundary

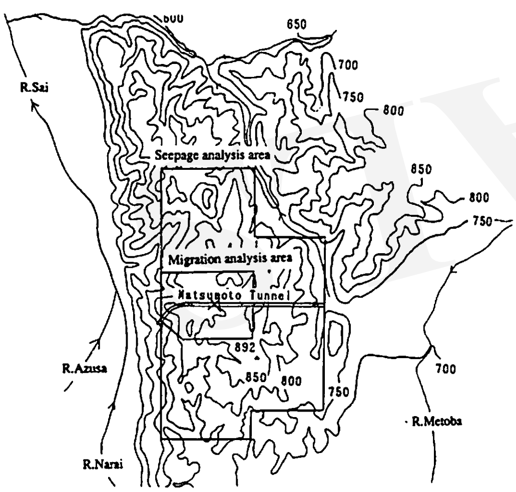


Fig. 12. Location of the Matsumoto tracer test.
×: Tracer injection borehole

Table 5. Parameters and boundary conditions used in the seepage analysis at the Matsumoto site.

Hydraulic conductivity	1×10^{-5}–5×10^{-3} cm/sec
Boundary conditions	Impermeable boundary (Except the tunnels and springs)
Tunnels Springs	Steady-state piezometric head level

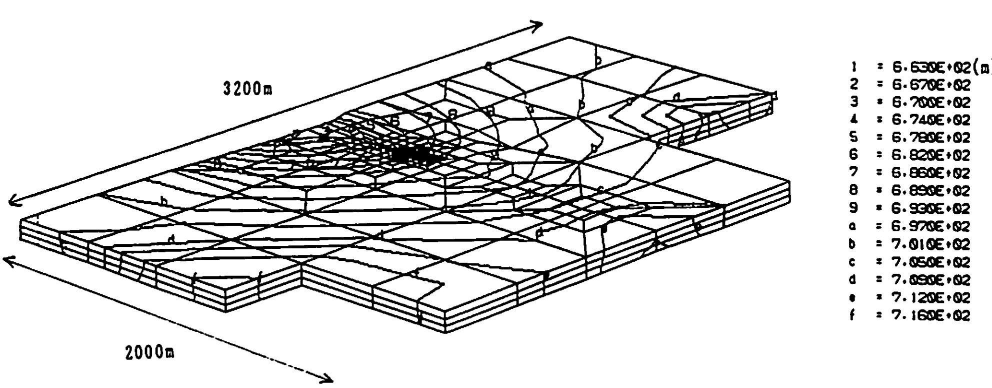


Fig. 13. Analytical model and analyzed piezometric-head distribution at the Matsumoto site.

conditions used in the seepage analysis. At the tunnel and springs, groundwater gushed out. The altitudes of tunnels and springs were assumed to be steady-state piezometric head levels. Figure 13 displays an analytical model for the seepage analysis and the distribution of analyzed piezometric-head values. These values were used to make a migration analytical model. The altitude of the west side of the tunnel was lower than that of the east side of the tunnel. In this analysis, we couldn't estimate hydraulic conductivity because flow rate conditions were not given.

(2) Migration analysis

A coupled equation governing groundwater flow and advection-dispersion in a three-dimensional system is given as follows,

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} + D\frac{\partial^2 C}{\partial y^2} + D\frac{\partial^2 C}{\partial z^2} - Vx\frac{\partial C}{\partial x} - Vy\frac{\partial C}{\partial y} - Vz\frac{\partial C}{\partial z} \quad (11)$$

$$Vx = vx/\varepsilon,\ Vy = vy/\varepsilon,\ Vz = vz/\varepsilon$$

where

ε: effective porosity, C: concentration, D: dispersion coefficient, Vx, Vy, Vz: actual velocity in the x, y and z directions, and vx, vy, vz: apparent velocity in the x, y and z directions.

Dispersion coefficient is given as follows,

$$D = \alpha |V|$$

where $|V|$: $\sqrt{Vx^2+Vy^2+Vz^2}$ and α: longitudinal dispersivity.

The dispersion coefficient depends on actual velocity and is isotropic. The system boundaries are impermeable except at the borehole.

$$F = F_0 \text{ at the borehole} \quad (12)$$

where

F: flux of mass ($\partial C/\partial t$), and F_0=flux of mass at the borehole.

A migration analysis was performed using FEM and the boundary conditions described by equation (12). The computer code used was developed by Kawamura.[8]

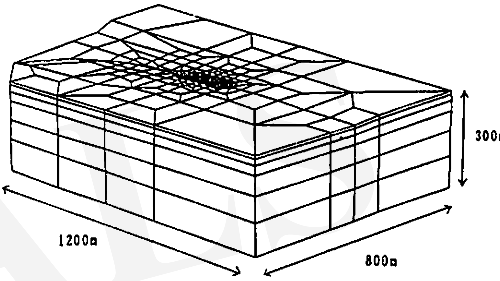
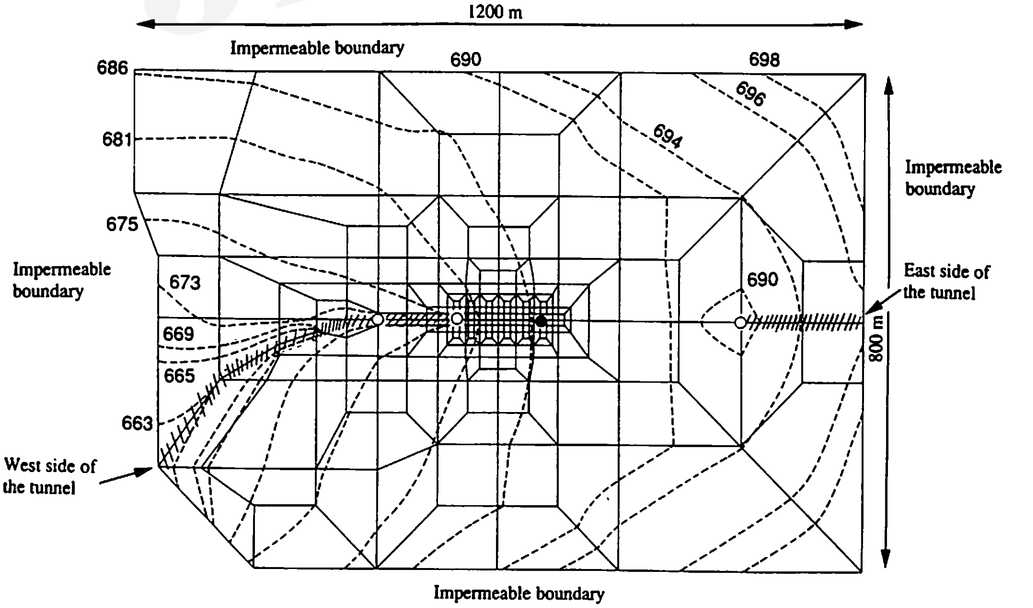


Fig. 14. Analytical model for the migration analysis at the Matsumoto site.



(○: Sampling point, ●:Tracer injection borehole, ////// :Tunnel)

Fig. 15. Analytical model for the migration analysis and analyzed piezometric-head distribution at the Matsumoto site (Horizontal section).

Figures 14 and 15 show an analytical model for the migration analysis and analyzed piezometric head distribution. Groundwater levels were coincided with the upper surface of the model. Table 6 displays the parameters and boundary conditions used in the migration analysis. Porosities of the core samples taken from the borehole were determined by weighing the sample in both water saturated and dry conditions. The porosity values ranged from 7 to 15%. Therefore, we assumed the maximum effective porosity was 15%. The tracer solution containing 23,289.6 g of Br^- (NaBr: 30,000 g) was injected at the borehole for 30 minutes.

3) Numerical results and discussion

Figure 16 shows the correlation between the concentration of Br^- in the tunnel seepage which is 130 m apart from the borehole and the time elapsed from the start of tracer injection.

Table 6. Parameters and boundary condition used in the migration analysis at the Matsumoto site.

Flux of mass (Br^-)	46,579.2 g/hour $0 \leq \text{time} \leq 30$ (minutes)
Effective porosity	Maximum 15%
Longitudinal dispersivity	5–100 m
Boundary condition	Impermeable
Hydraulic conductivity	1×10^{-5}–5×10^{-3} cm/sec

The relationship was obtained from the three-dimensional FEM migration analysis. Effective porosity, longitudinal dispersivity and hydraulic conductivity were determined to be 0.4%, 9 m and 6×10^{-2} m hour^{-1}(1.7×10^{-3} cm sec^{-1}). If tunnel seepage is free water in the rocks unsaturated during tunnel construction, effective porosity is calculated to be 0.6% by the equation $\varepsilon = Qt\ Vr^{-1}$. The concentration of tritium indicated tunnel seepage was not surface water but groundwater stored in the rocks for more than 50 years.[9] *Qt* represents the total volume of the tunnel seepage. *Vr* represents the total volume of the rock unsaturated during tunnel construction. The calculated effective porosity coincides with the analyzed effective porosity. The effective porosity value is smaller than the porosity value and is useful for an estimation of storage volume. Figure 17 indicated longitudinal dispersivity at the Matsumoto tracer test coincided with Leonhart *et al.*[1] results. The Lugeon tests results using the borehole indicated hydraulic conductivity values ranged from 1×10^{-5} to 5×10^{-4} cm sec^{-1}. The analyzed hydraulic conductivity value is larger than those of the Lugeon test. Lugeon test indicates a hydraulic conductivity only around a borehole. As test scale increases, hydraulic conductivity increases.

Figures 18, 19 and 20 show Br^- concentration distributions analyzed by FEM using 9 m longi-

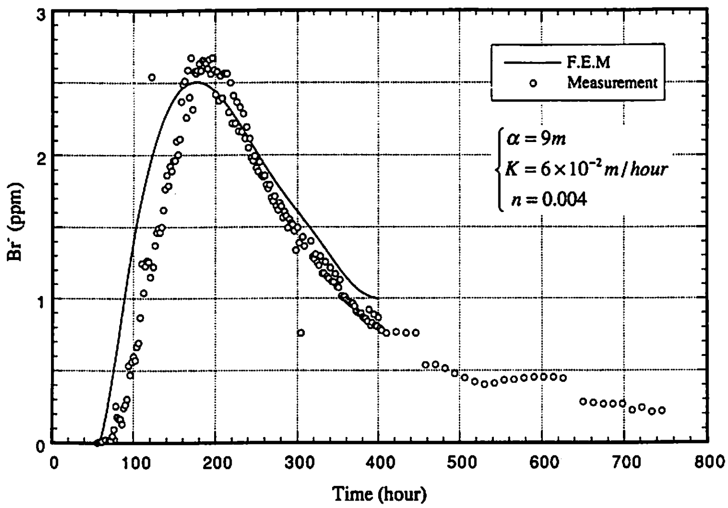


Fig. 16. Relationship between elapsed time after the start of tracer injection and concentration of Br^- in the tunnel seepage which is 130 m apart from the borehole at the Matsumoto site.

tudinal dispersivity, 0.4% effective porosity and 6×10^{-2} m $hour^{-1}$ hydraulic conductivity, 40, 100 and 300 hours after the start of tracer injection. The Br^- concentration peak moves towards the cutting face at the west side of the tunnel and the Br^- concentration reduces in progression.

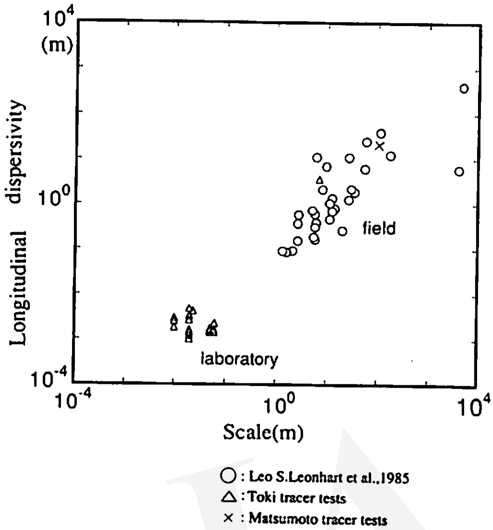


Fig. 17. Relationship between longitudinal dispersivity and test scale.

5. Bentonite and Quartz-sand Mixture Laboratory Tracer Tests

1) Material

Samples used in this test were composed of Kunigel bentonite, marketed in Japan by Kunimine Industries Co., LTD., and Flattery quartz-sand, from Australia. The samples used had bentonite to quartz ratios of 1 : 9. Mineralogical analysis, using an X-ray diffractometer determined that the bentonite was composed of approximately 60% montmorillonite, 30% quartz, and 5% feldspar. Flattery sand is 99% quartz.

Figure 21 shows the grain size distribution curves for bentonite and quartz-sand. Grain sizes smaller than 0.044 mm were measured using the Andreasen pipette method. Grain sizes greater than 0.044 mm were measured with a sieve under dry conditions. The bentonite consisted of very fine grains, with an accumulation content of more than 50% for grains smaller than 0.002 mm. Large grains, 0.1 to 0.3 mm, are characteristic of the quartz-sand.

The porosity of the sample must be determined initially in order to compare effective porosity with porosity. Porosity can be calcu-

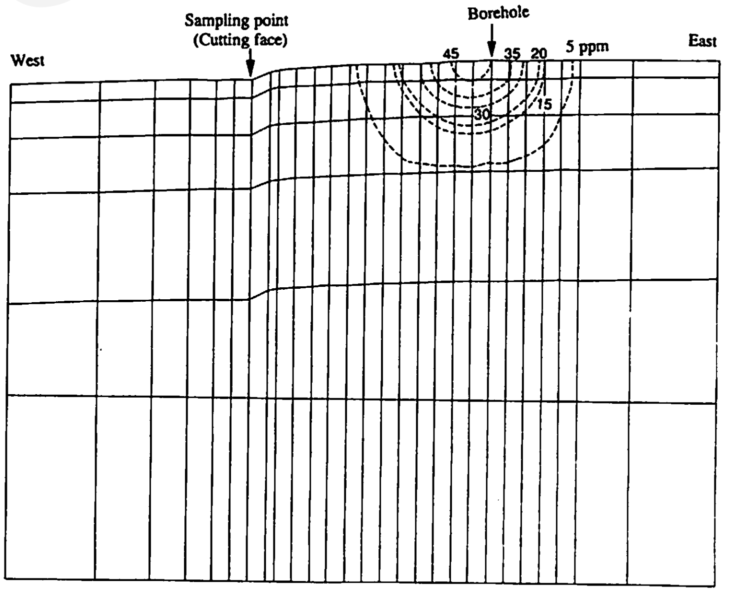


Fig. 18. Analyzed Br^- concentration distribution 40 hours after the start of tracer injection at the Matsumoto site.
Sectional plan, $\varepsilon=0.4\%$, $\alpha=9$ m, $K=6\times10^{-2}$ m $hour^{-1}$

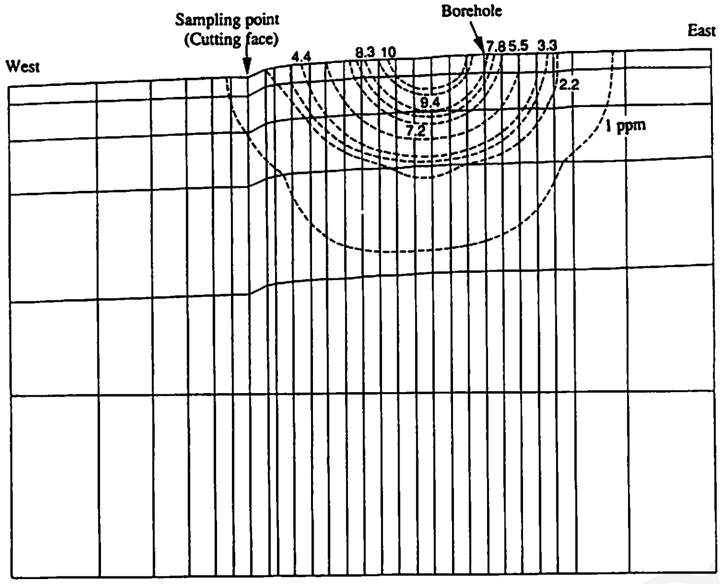


Fig. 19. Analyzed Br^- concentration distribution 100 hours after the start of tracer injection at the Matsumoto site.
Sectional plan, ε=0..4%, α=9 m, $K=6\times10^{-2}$ m hour^{-1}

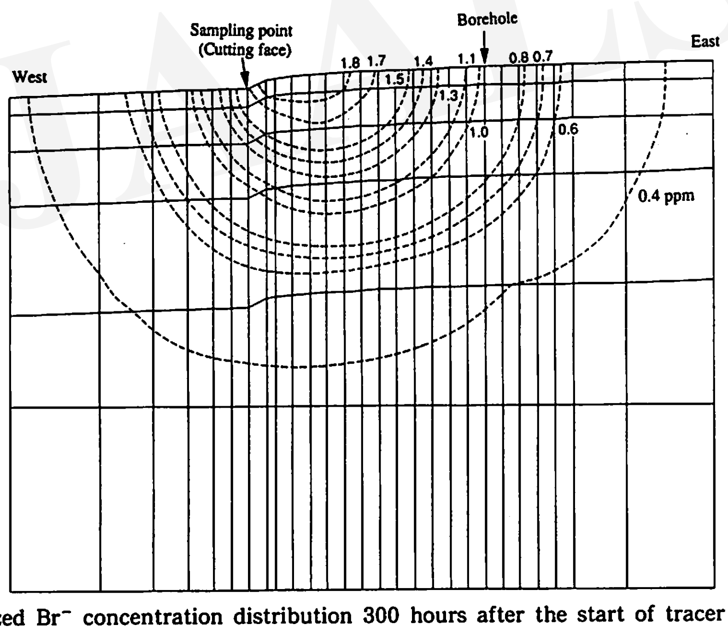


Fig. 20. Analyzed Br^- concentration distribution 300 hours after the start of tracer injection at the Matsumoto site.
Sectional plan, ε=0.4%, α=9 m, $K=6\times10^{-2}$ m hour^{-1}

lated using true gravity density and dry density values. As the true gravity density values for bentonite and quartz sand, and therfore for all of the mixture samples, were very similar, the porosity for all three samples was established from the density values of one representative sample. For the sample with a 10% bentonite to 90% quartz sand ratio, the true gravity density is 2.61 g cm^{-3}. The maximum porosity of the bentonite and sand mixture was calculated to be 43%, using the following formula:

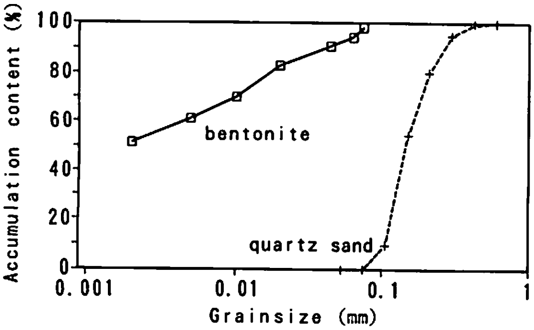


Fig. 21. grain size distribution curve of bentonite and quartz sand.

$$\text{Porosity } (\%) = (1 - Pd \div G) \times 100 \qquad (13)$$

where

Pd: dry density and *G*: true gravity density.

2) Method

Bentonite and quartz sand mixtures were placed in a metallic or acrylic resin cylinder with an inner diameter of 5 cm. The samples were compacted by an unconfined pressure apparatus. The sample material had a dry density of 1.5 g cm^{-3}, a water content of 5%, and a mixture ratio of bentonite to quartz-sand of 1 : 9. The height of the compacted samples was adjusted to achieve a fixed porosity. A tracer solution was pumped into the column under a constantr flow rate. The tracer concentration in the effluent solution was analyzed with ion exchange chromatography.

The Toki laboratory tracer tests and the bentonite and quartz-sand mixture laboratory tracer tests used the same method of analysis.

3) Results

Table 7 gives the conditions and results of the bentonite and quartz-sand mixture laboratory tracer tests. Effective porosities ranged from 13 to 44%. In some cases, the maximum effective porosity value corresponded to the porosity. Figure 22 shows the relationship between effective porosity and hydraulic conductivity. Despite a constant porosity value, the hydraulic conductivity values changed from 1.0×10^{-8} to 1.4×10^{-7} cm sec^{-1}. However, samples varied with respect to pore geometry. As the hydraulic conductivity increased, the effective porosity decreased. This was seen as strange because as the areas that water can flow through increase, generally the flow rate and hydraulic conductivity increase. When using the same porosity conditions, only pore geometry and pore size distribution can differ between samples. Next, a relationship between pore size and acumulation porosity for the samples was investigated to clear up the inconsistency.

6. Pore Size Measurement of Bentonite Quartz-sand Mixture

When a dye solution was pumped into soil column, dyed areas indicated flow paths. The flow path variation between samples depended on pore geometry. Therefore, pore size distribution for dyed areas and undyed areas was measured.

1) Method

After the effective porosity test was com-

Table 7. Conditions and results of column experiment of bentonite and quartz-sand mixture.

Dry density (g cm^{-3})	Mixture ratio	Flow rate (cm^3 sec^{-1})	Tracer	Actual velocity (cm sec^{-1})	Dispersion coefficient (cm^2 sec^{-1})	Effective porosity (%)	Hydraulic conductivity (cm sec^{-3})
1.5	10:90	1.1×10^{-4}	Cl^-	1.3×10^{-5}	2.5×10^{-5}	43	1.0×10^{-8}
		5.0×10^{-4}	Cl^-	1.1×10^{-4}	5.0×10^{-5}	23	4.4×10^{-8}
		6.1×10^{-4}	Cl^-	1.7×10^{-4}	$2{,}2\times10^{-4}$	18	5.2×10^{-8}
		5.8×10^{-4}	Cl^-	2.4×10^{-4}	1.7×10^{-4}	13	1.0×10^{-7}
			Br^-	2.3×10^{-4}	1.8×10^{-4}	13	
		1.6×10^{-3}	Cl^-	6.1×10^{-4}	7.7×10^{-4}	13	2.4×10^{-7}
	7:93	3.1×10^{-4}	Br^-	6.5×10^{-5}	1.2×10^{-4}	24	2.5×10^{-8}

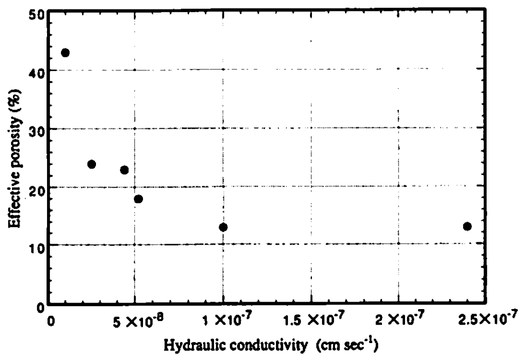


Fig. 22. Relationship between effective porosity and the hydraulic conductivity of the bentonite and quartz sand mixture.

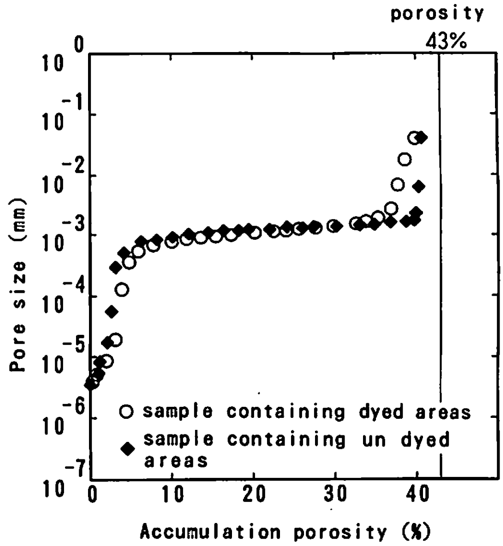


Fig. 23. Relationship between pore size and accumulation porosity.

pleted, the tracer solution in the laboratory feed tank was replaced with a solution containing dye. This solution was pumped into the soil column. When the dye appeared in the effluent solution, indicating that it had passed through the sample, the cylinder was dismantled. The sample was then quick frozen in liquid nitrogen and dried using a vacuum pump at the temperature of less than 0℃. The quick-freezing process fixed the texture of the sample, and worked to avoid the shrinkage that occurs when bentonite is dried at normal temperatures. The dried sample was cut into rectangular sections with sides less than 1 cm long. Two types of rectangular sections were cut: one containing dyed areas indicating the flow path of the colored solution, and the other containing areas where no dye was present. The porosity of the dried sample sections was measured using a mercury pressure porosimeter which determines porosity for pores smaller than 0.1 mm. This porosity measurement assumes that pores are cylindrical in shape. The porosity and the accumulation porosity were determined from the pressure and volume of the mercury forced into the sample. The relationship between pore diameter and pressure is as follows:

$$r=2\times T\times \cos O\div P \qquad (14)$$

where

r: diameter of pore, T: surface tension of mercury, O: contact angle, and P: pressure.

2) Results and discussion

Figure 23 presents the relationship between pore size and accumulation porosity for the two types of rectangular sections. Pores smaller than 0.001 mm in size were seen to characterize the medium accounting for 70% of all pores. The accumulation porosity for this pore size was found to be about 30%. A comparison of Fig. 21 and Fig. 23 reveals that a pore size smaller than 0.1 mm, which corresponds to the grain size of bentonite, makes up more than 90% of all void areas. However, a pore size greater than 0.1 mm, the grain size of qauartz sand, is very rare. The gaps between the large grains of the quartz-sand seem therefore to be closed by the bentonite. The flow sections, or dyed areas, had a larger proportion of pores between 0.001 mm and 0.1 mm (the grain size of bentonite) than the section with no evidence of a flow path. The flow paths seemed to result from an irregular distribution of bentonite in the sample.

As seen in Fig. 23, the results revealed differences between the two types of rectangular sections. Five percent of the sections containing dyed areas had pore sizes greater than 0.001 mm contrasted with only 1% of the undyed sections. However, the accumulation porosity for pore sizes smaller than 0.1 mm in the section without dyed areas varied little from that in the section with dyed areas. Therefore even at the same porosity condition, the pore size in flow path areas was larger than in no-flow path areas. If the shape of the pores is regarded as cylindrical, the flow rate is given as follows,

$$Q=\frac{\pi r^4}{8\mu}\rho gi$$

$$\frac{Q}{\pi r^2}=\frac{r^2}{8\mu}\rho gi \qquad (15)$$

where

r: radius, μ: coefficient of viscosity and ρ: water gravity density.

If the shape of the pores is regarded as rectangular, the flow rate is given as follows,

$$Q=\frac{w^3L}{12\mu}\rho gi$$

$$\frac{Q}{wL}=\frac{w^2}{12\mu}\rho gi \qquad (16)$$

where

L: length and w: width.

The flow rate per unit pore area is in proportion to the square of r or w. Therefore, as pore dimensions increase, with porosity held constant, the flow rate becomes larger. Even under the same porosity conditions, hydraulic conductivity changes depending on pore size distribution. As the contrast between pore sizes, within a sample, increases, the total flow through the sample approaches the amount of flow through the large pores only and the flow through the small pores becomes negligible. As a result, effective porosity become smaller. Therefore, under constant porosity conditions, as the large pores increase in size, hydraulic conductivity increases and effective porosity decreases.

7. Discussion

The effect of test scale on effective porosity was considered by comparing field tracer test results and laboratory tracer test results. Figure 24 shows the relationship between effective porosity relative to porosity, and test scale. Test scale was defined as the length of the sample in the laboratory tests and the distance between the tracer injection point and the sampling point in the field test. The ratio of effective porosity to porosity indicates the proportion of pore volume through which solution actually flows to total pore volume. As the test scale increased from 1.0 cm to 130 m, effective porosity relative to porosity decreased from 100 to less than 5%.

At the Toki site the result of the field permeability test between the two boreholes used for the field tracer test[10] showed that the hydraulic conductivity of the permeable layer was 2×10^{-5} cm sec^{-1}. This value was much larger than those estimated in the laboratory tests, which were 2×10^{-8}–4×10^{-7} cm sec^{-1}. In the laboratory tests, borehole core samples with no cracks were used. If a crack had existed in the core sample, the sample would have separated at the crack. It a fracture with a width of 0.1–0.2 mm existed at the field scale, the mean hydraulic conductivity of a 10 m zone would be 2×10^{-5} cm sec^{-1} based upon the Hele-Shaw model. The occurrence of fractures do not

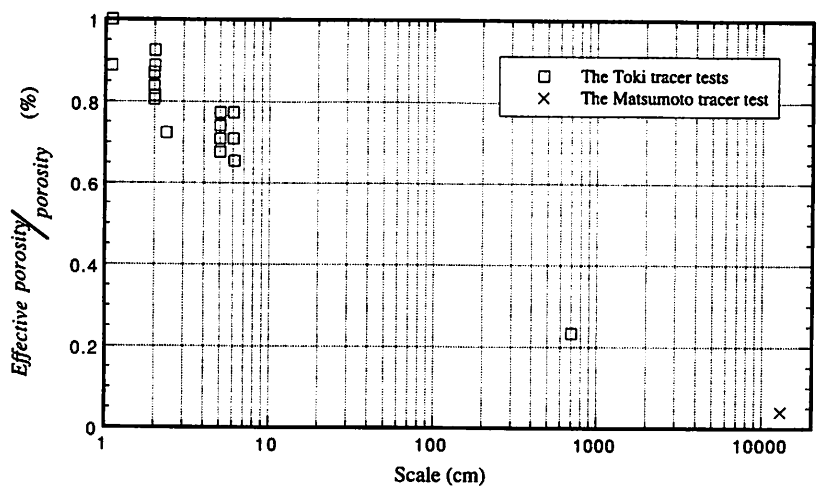


Fig. 24. Relationship between effective porosity relative to porosity and test scale.

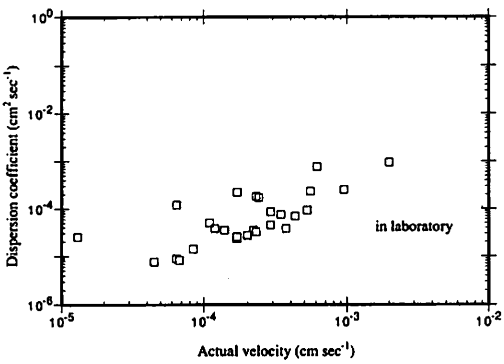


Fig. 25. Relationship, estimated in laboratory tests, between the dispersion coefficient and actual velocity.

greatly influence the porosity of the zone. Therefore, it is possible that permeable cracks or fissures existed at the Toki field site. In the same way at the Matsumoto site, as test scale increases, hydraulic conductivity increases. The number of permeable cracks or fissures are thought to increase as test scale increases. From the laboratory scale to the field scale, the decrease in effective porosity and increase in hydraulic conductivity was due to the increase of cracks or fissures according to the bentonite and quartz sand mixture laboratory test results. On the laboratory scale, the decrease in effective porosity was probably due to a loss of connectivity of continuous pores as neither cracks nor fissures were present in the samples.

Figure 25 shows the relationship, estimated in laboratory tests, between the dispersion coefficient and actual velocity. As the actual velocity increases, the dispersion coefficient increases. Figure 17 shows the relationship between the test scale and longitudinal dispersivity in sedimentary rocks. Longitudinal dispersivity is the dispersion coefficient divided by actual velocity. Originally Leonhart *et al.*[1] showed that as the scale of field tests increased, longitudinal dispersivity increased. Our results and the Leonhart *et al.*[1] results indicate that as the test scale increases from laboratory scale, several centimeters, to field scale, several thousand meters, longitudinal dispersivity increases proportionally. The following empirical relationship has been found from these results: longitudinal dispersivity equals one tenth of test scale.

On the sample scale, an increase in longitudinal dispersivity has not been detected. According to the effective porosity discussion, selective flow paths such as cracks and fissures may exist at the field scale. The existence of selective flow paths possibly affects the increase of longitudinal dispersivity, but quantitative estimation of the influence has been impossible due to the lack of information concerning the geometry and character of the selective flow path.

8. Conclusion

We have performed both laboratory and field tracer tests using conservative tracers in order to estimate the effective porosity and longitudinal dispersivity of a sedimentary rock. Both the laboratory and field tracer test results indicate that as test scale increases from 1.0 cm to 130 m, effective porosity decreases and longitudinal dispersivity increases. The following empirical relationship has been found for the sedimentary formation: longitudinal dispersivity equals one tenth of scale. The relationship is useful for estimating mass transport in groundwater.

The decrease in effective porosity may be attributed to the loss of continuous pore connectivity at the laboratory scale and the increase of selective flow path such as cracks and fissures from laboratory scale to field scale. The existence of selective flow paths such as cracks and fissures has been suggested based on the results of field permeability tests. The lower effective porosity encountered at the field scale may be attributed to the existence of selective flow paths not present in the laboratory samples. At the laboratory scale, the decrease in effective porosity was probably due to a loss of continuous pore connectivity. But the effect of selective flow paths on the increase of longitudinal dispersivity has not been quantified due to the lack of information concerning the geometry and character of the selective flow paths.

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A Non-irrigation System Using the Dew Condensation Caused by Diurnal Range of Air Temperature in Arid Sand Dune Area

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1. Introduction

About 30% of the whole land on the earth is arid or semi-arid which are generally too dry to produce a good crop yield. As a consequence of recent investments of a huge amount of money for irrigation, the total arable land area of arid regions in the world has increased much. On the other hand, delivering a large amount of irrigation water into dry land has caused a rise of underground water table and much of the arable irrigated land has suffered from soil salinity (MATSUMOTO, 1988[1]). Once salinity and alkali hazard in the soil surface are established, growth of plants is checked severely and desalinization of the soil with irrigation water becomes practically impossible.

After all, to maintain a sustainable agriculture in arid land without accumulating salts is how to get good quality water and to apply it conservatingly. A number of plans based on this idea has been proposed. We have also planned a water-harvest system by dew condensation using the natural phenomenon that difference between air and soil temperature in arid sand area is very large (MATSUMOTO *et al.*, 1993[2]). If evaporation from surface of arid sand is restricted, soil water could be gathered partially inside the rhizosphere and plants will be able to grow in much better moisture condition. According to this plan, the fundamental examination was undertaken and some results from the experiment were obtained. Through the experimental data, we have confirmed the idea that water harvesting system is possible in arid sand dune area for a practical greening method.

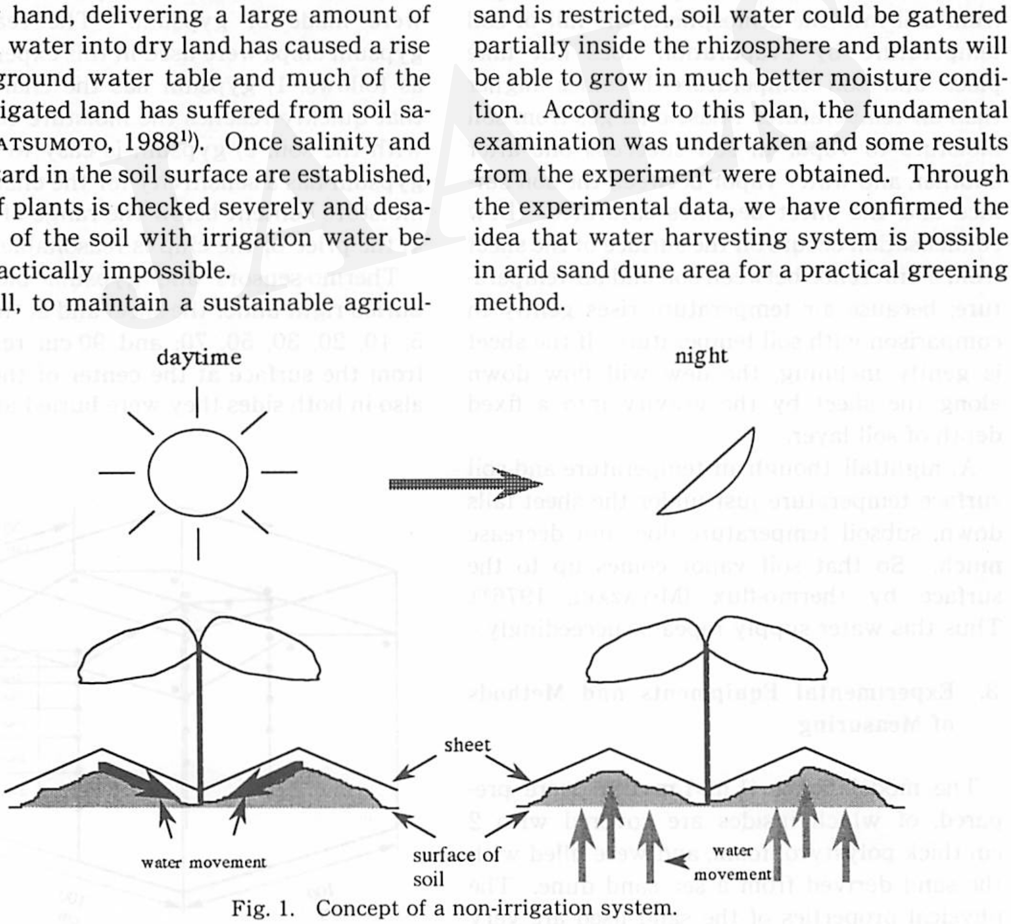

Fig. 1. Concept of a non-irrigation system.

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2. The Concept of the Non-irrigation System

Plastic mulching is utilized worldwide nowadays (TAKAKURA, 1993[3]). The main purposes of using the plastic mulch are restricting water evaporation and keeping the soil surface warm. In this non-irrigation system, plastic mulching is more actively intended to collect water. Under the condition that evaporation is restricted by the plastic sheet, the movement of soil moisture without gravity water is exclusively only that of vapor in the nonisothermal and condensing process (Nasser and Horton, 1989[4]). Soil vapor movement and the potential of water harvesting is shown in Fig. 1.

The heat from the sun through transparent plastic sheet changes soil moisture into vapor. As the sheet restricts evaporation of vapor from soil into the atmosphere, the fall of soil temperature by evaporation does not take place and soil temperature becomes higher than air temperature. Phase changes from soil moisture to vapor in soil succeeds one after another, and water vapor between the soil surface and the sheet becomes saturated. Dew condensation occurs on the surface of the sheet from a difference between soil and air temperature; because air temperature rises gently in comparison with soil temperature. If the sheet is gently inclining, the dew will flow down along the sheet by the gravity into a fixed depth of soil layer.

At nightfall, though air temperature and soil surface temperature just under the sheet falls down, subsoil temperature does not decrease much. So that soil vapor comes up to the surface by thermo-flux (MIYAZAKI, 1976[5]). Thus this water supply repeats succeedingly.

3. Experimental Equipments and Methods of Measuring

The model boxes (1 m*1 m*1 m) were prepared, of which insides are covered with 2 cm-thick polystyrol foam, and were filled with the sand derived from a sea sand dune. The physical properties of the sand used are very similar to the sand in Mao-niaosuhu desert of China, and the water content of the sand was adjusted to the lightly moistened condition (about 10%) by drying under the sunlight. Observation windows were set in front of the boxes.

For producing the dew insides of the plastic sheet, the sheet was buried at the depth of 2–3 cm from the surface of the sand soil with the top gently inclining to the both sides of the box. In order to collect the dew, small gutters were set at both ends of the sheet. As the box was also equipped with 500 W electric lamps, the change of temperature and the production the dew were controlled. The lamps were lit from 8 : 00 am to 5 : 30 pm daily.

In order to understand movement of soil moisture, soil temperature and soil moisture content were measured respectively by a thermocouple and an electric resistance using platinum electrodes. Sensor chips for soil moisture were made of gypsum. The reason why gypsum chips were used in this experiment are as follows: 1) gypsum has the characteristics that quickly reaches the moisture equilibrium with the soil, 2) gypsum is easy to handle, 3) gypsum has a sensitivity for the change of soil moisture content below the range of 10%, and 4) the price of the chip is reasonable.

Thermo-sensors and gypsum blocks were buried right under the sheet and at the depth of 5, 10, 20, 30, 50, 70, and 90 cm respectively from the surface at the center of the box and also in both sides they were buried at the same

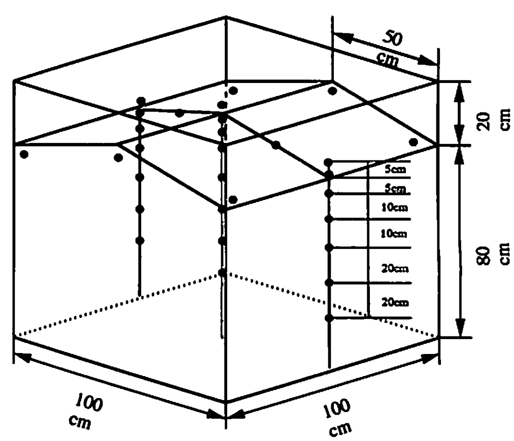

Fig. 2. Location of thermocouples and gypsum blocks.

interval to 70 cm depth (Fig. 2). Electric resistance was measured once a day and soil temperature was followed automatically.

The experiment was carried out from October 13 to December 20, 1992. Fig. 3 shows changes in air temperature on October 24, 1992. Figure 4 shows the dynamics of electric resistance. When the experiment was completed, soil samples were collected around the chips and their moisture content determined in order to relate electric resistance to moisture content.

4. Results and Discussion

1) Changes of soil temperature

Using 500 W lamps, diurnal range of topsoil temperature reached about 30℃ in comparison to about 25℃ of air temperature (Fig. 3). The distance influenced due to daily range of air temperature was about 30 cm depth from the surface. Temperature being controlled by the lamps in this experiment, the air temperature continues to rise until 5 : 00 pm. Just after the time the lamps were turned off, temperature

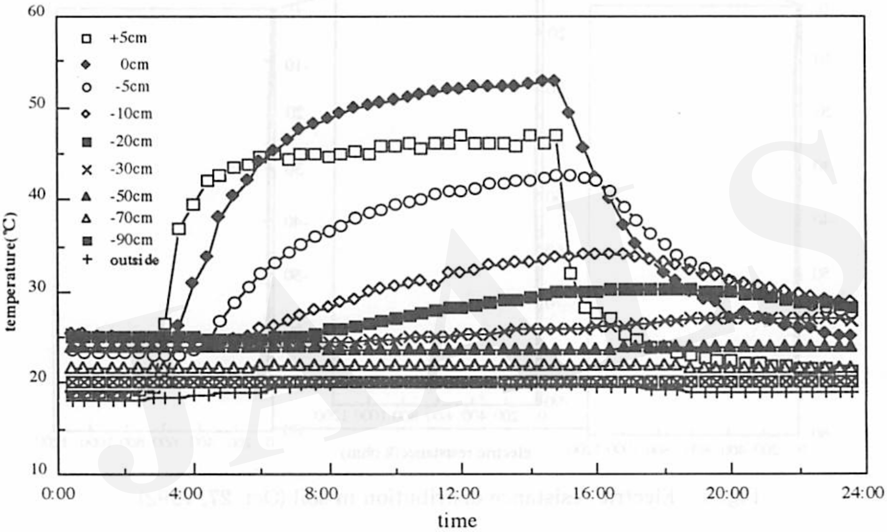

Fig. 3. Changes of soil and air temperature for a day.

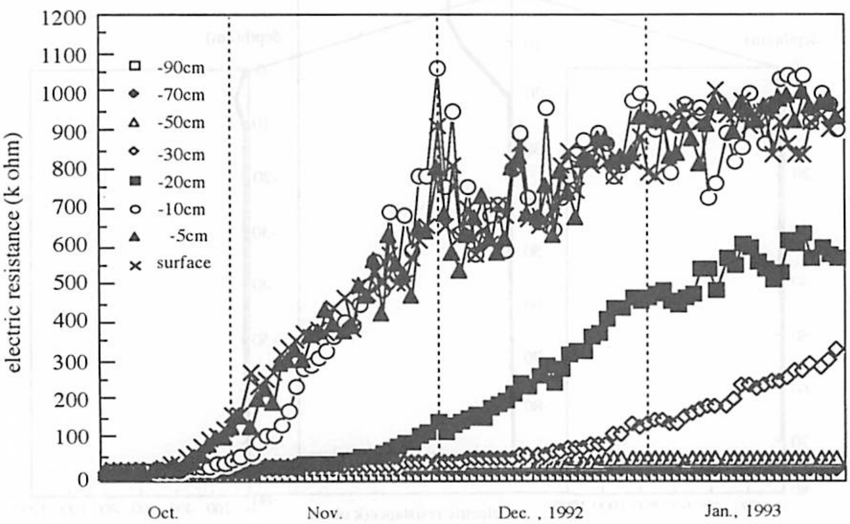

Fig. 4. Changes of electric resistance at the center of the sheet.

dropped down quickly and the difference between air and soil temperature approach not less than 20℃. The amount of dew condensing at this time was the largest throughout the duration time.

During lights-out, temperatures of atmosphere around the equipment and topsoil were lower than that of the subsoil. The temperature difference between the atmosphere and subsoil will lead to the reversal of movement of soil vapor and the vapor ascend from the deeper to upper soil layer.

2) Changes of soil moisture

Electric resistance in the center of the box was larger as measuring point became upper (Fig. 4). It means that the topsoil was drier as time passed. After the resistance value became

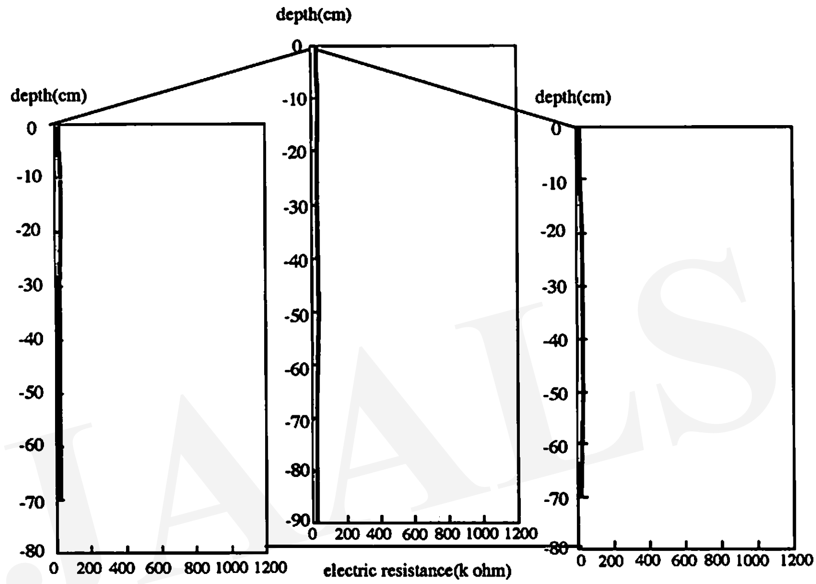

Fig. 5. Electric resistance distribution in soil (Oct. 27, 1992).

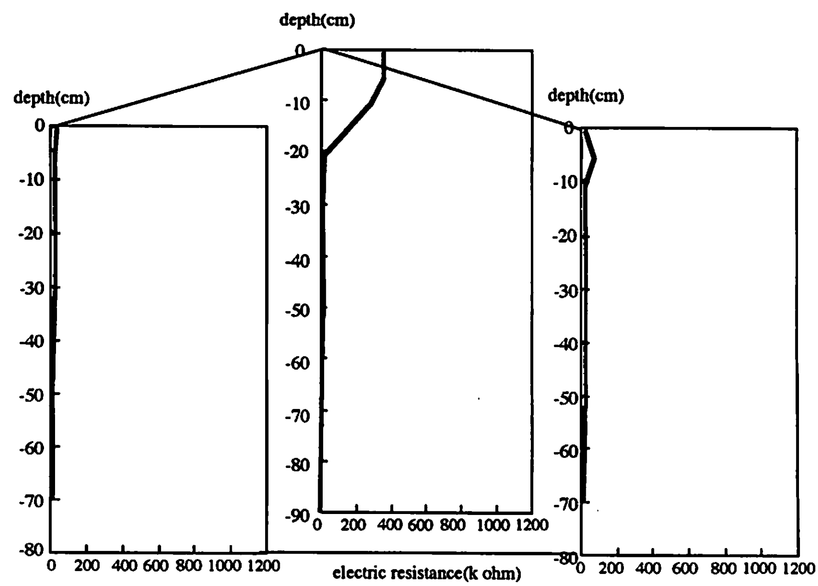

Fig. 6. Electric resistance distribution in soil (Nov. 25, 1992).

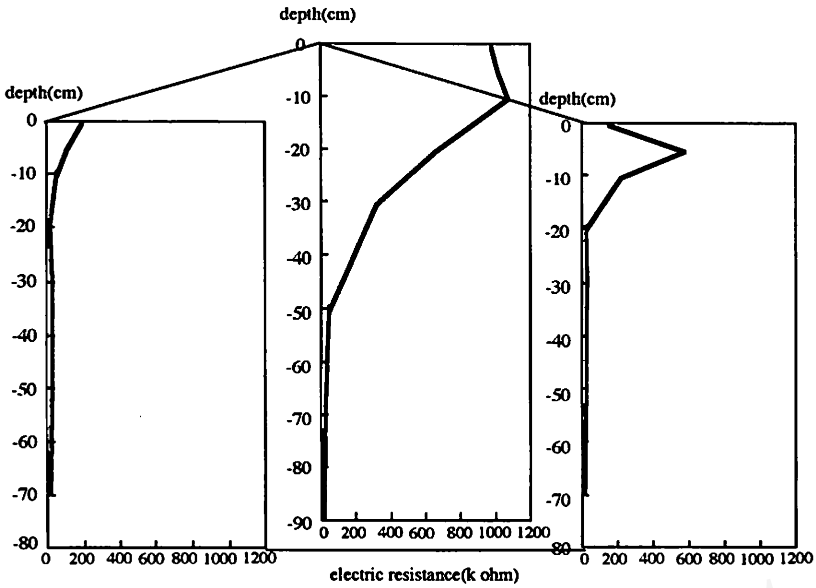

Fig. 7. Electric resistance distribution in soil (Dec. 15, 1992).

more than 500 k ohm, it changed greatly up and down by very small amount of soil water. Dry sand layer does not happen in actual arid sand dune unlike in the model examination, as soil vapor is thought to move from the sides.

Electric resistance changed very little on the sixth day from the beginning of the experiment (Fig. 5). A pentagon in the figure shows the box plate outside and the shape of the sheet.

Figure 6 shows the distribution of electric resistance on the 27th day. The resistance value from surface to 20 cm depth in the center showed larger than at both sides. This fact means the water movement from the center zone has occurred and became drier.

Figure 7 shows the distribution of electric resistance on the 95th day. The distribution of electric resistance is almost as the same depth pattern as the diurnal range of temperature. Soil water movement was recognized clearly, and near the sheet, electric resistance value was reversed. This fact shows that the upper layer is more wet than the lower layer.

Ohte (1992)[6] reported that the soil depth influenced by the diurnal range of soil temperature corresponds to the depth of dry sand layer. Through the experiment, the process of producing dry sand layer was confirmed. Dew condensation is a phenomena which occurs when humidity is more than 100%. So if soil water becomes condensed, the system should be made as closed as possible. The sand box was tightly enclosed with the sheet, however a little opening apparently part allowed soil moisture to leak out to atmosphere where the sensor wires were connected.

3) Water content and electric resistance

Water content is related to electric resistance. Using the gypsum chips, we computed the relationship between water content and electric resistance as follows:

$$\log y = -0.35x + 4.48$$

(x: water content, y: electric resistance)

The corelation coefficient (r^2) was 0.72. The reason why the corelation coefficient was low is that individual characteristics of each gypsum chip was not compensated under a fixed temperature.

4) Dew on the sheet

The condensed water could not be quantified on the plastic sheet, however, the sum of the harvested water was measured, and it was about 300 ml from an entire box.

Dew on the sheet was relatively large until the 70th day, however it decreased day by day. The reason being, the total amount of water in the soil had fallen. In actual dry sand area, this decrease of soil water dose not seem to happen because soil vapor movement from the sides will continuously supplied.

5) Shape of the sheet

The model box was covered with the waving sheet of vinyl chloride gently inclining to both sides of the box (Fig. 2). It is thought to be better to keep the sheet and sand untouched for the purpose of collecting the dew, preventing dew from being absorbed by the sand. Though a waving sheet was used this time, another shape for dew to flow more easily is needed.

The gradient was of 2 in 5 in the model box. Taking into consideration for balance between heat and water flowing, the gradient should be determined. Furthermore, a better canopy shape of plastic sheet is needed for more effective collection of dew, for instance, funnel shaped sheet.

6) Observation through the front window

We could observe the movement of soil moisture as change of soil color through the window. And at the same time, it could be found out that soil water tends to move around the walls and wires. This observation means that water moves toward the border of soil and different kind of material.

7) Collecting water in the gutter

It could roughly be estimated the volume of water movement under a plastic sheet caused by the thermo-flux. Our calculation showed that the volume of water concentrated to move was about 300 ml from 1 m^2. This 300 ml of collected water per m^2 for three months is enough for the germination of plant seeds, however it is difficult to grow plants by only this non-irrigation system. Effective combination of other greening systems are needed.

Lastly, though this non-irrigation system is in its initial stage; potential of water harvesting appears promising in sand dune area. It is our hope that this system could contribute to the establishment of vegetation in desertified areas. In order to introduce the system, climatic characteristics of the region and effective combination of other desertification protection technologies have to be examined.

And in future, we think that this non-irrigation system can take an important part in greening technology fitting the natural desert ecosystem.

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Saline Drain Water Reuse in Agroforestry Systems

Kenneth K. TANJI*

1. Introduction

About one-third of the nearly 1 million ha of irrigated land in the west side of the San Joaquin Valley of California are waterlogged and salt-affected, and its shallow ground waters are saline and contain potentially toxic trace elements such as selenium and boron. Moreover, only about one-fifth of this irrigated land has opportunities to discharge its drainage waters into the Pacific Ocean through the San Joaquin River (SJVDP, 1990[1)]). An investigation was carried out to study the potential of agroforestry systems to reuse poor quality subsurface drainage waters and thereby relieve the drainage problem (Tanji and Karajeh, 1993[2)]).

Figure 1 presents a concept to reuse waters in the San Joaquin Valley until no longer usable (SJVDP, 1990[1)]). In this scheme the volume of drain waters is progressively reduced and its salt concentration is progressively increased for more economical management of the drainage problem. This paper reports on a set of data obtained from a eucalyptus tree plantation which consumed saline drain waters from an adjacent cropland.

2. Experimental Layout and Observations

Figure 2 shows the layout of the 11.45 ha agroforestry system at the Mendota site in the San Joaquin Valley. The 9.43 ha tree plantation consists of 89 rows of Eucalyptus camendulensis planted in 1985–86. The agroforestry

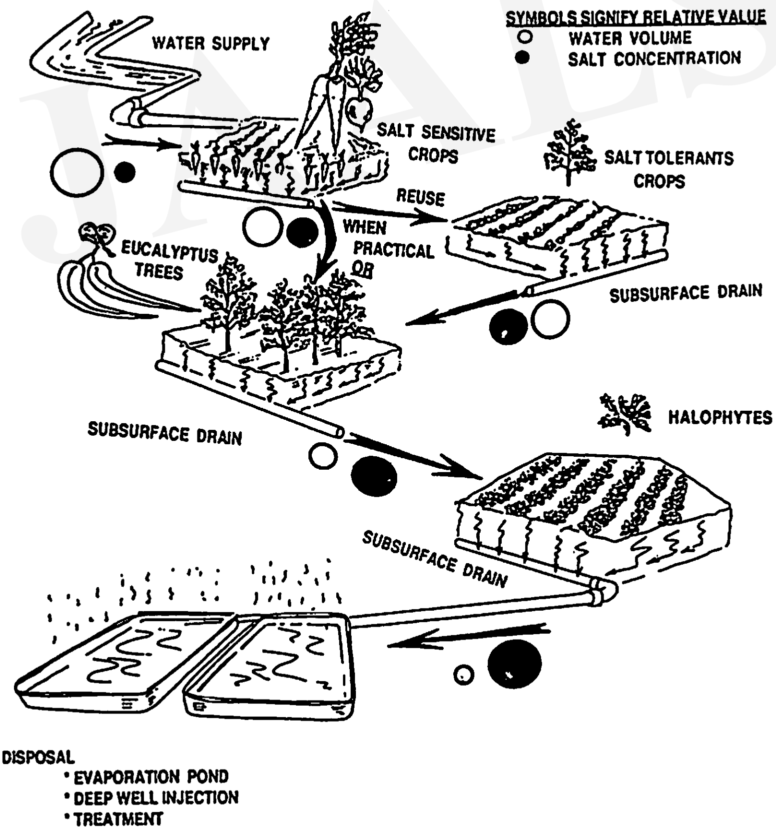

Fig. 1. Drainage-water reuse concept (SJVDP, 1990).

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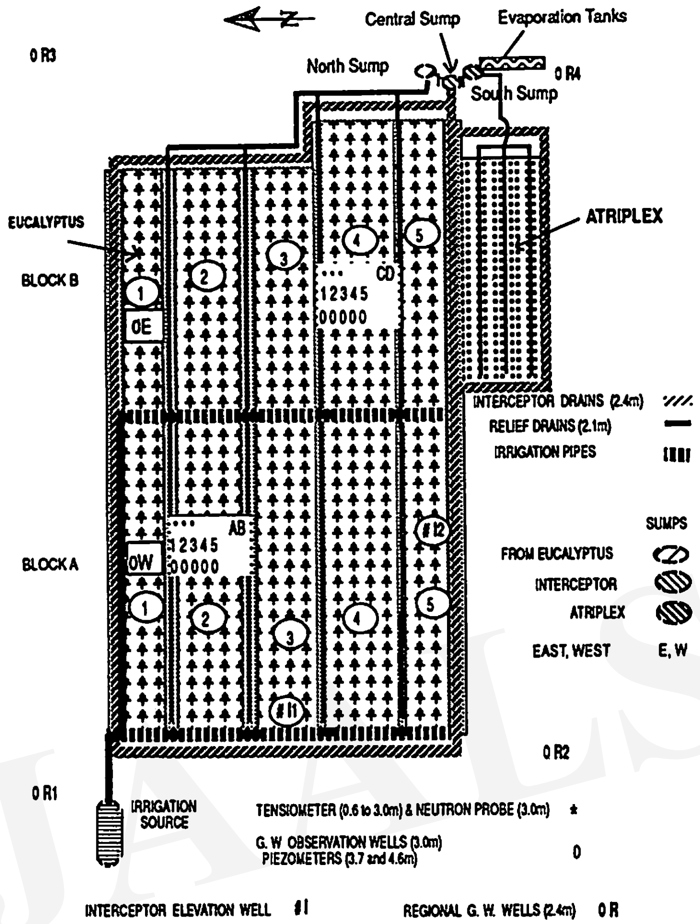

Fig. 2. Layout of experimental agroforestry system, Mendota, CA.

system also consists of a 2.02 ha plot of Atriplex spp., a halophyte, which was irrigated with subsurface drain waters from the tree plantation. The waterlogged experimental site contains fine textured silty clay loam soil underlain by an impermeable clay layer at the 3.0–3.7 m depths over the entire plantation. Both the tree and halophyte plots have perimeter interceptor drains and within-the-plot relief drains at 2.8 and 2.3 m depths, respectively. This underdrainage setup helps isolate the experimental site from surrounding lateral subsurface lateral flows and allows for monitoring water and salt flows within the experimental site. Saline subsurface drainage waters from nearby croplands are used to irrigate the eucalyptus. The tree plantation is furrow irrigated through gated pipes in two blocks in an easterly direction. The subsurface drainage from the trees are used to irrigate the Atriplex. The subsurface drainage from the Atriplex are collected into evaporation tanks and salts are harvested for disposal and/or reuse. Fig. 2 also gives other details on the experimental layout such as locations of observation wells to monitor water table elevations, tensiometers to measure soil-water pressures, access tubes for neutron probe to measure volumetric soil water contents, and piezometers to measure the hydraulic heads.

An agroclimatic station is located about 2 km away, and crop coefficient rates for evapotranspiration were measured on site by the Bowen ratio energy balance method (Dong *et al.*, 1992[3]). Applied waters and subsurface drainage were chemically characterized. The salinity status of the soils were measured by soil sampling as well as by a salinity probe and

Table 1. Chemical characteristics of irrigation and drainage waters

Description	EC (dS/m)	Na (ppm)	SO_4 (ppm)	Cl (ppm)	B (ppm)	Se (ppb)	SAR
Irrigation water, eucalyptus	10.0	1,638	3,236	1,196	12	396	11
Tile drain, eucalyptus	32.4	7,899	13,193	5,054	51	700	69
Tile drain, Atriplex	29.9	8,325	12,372	4,729	56	665	56
Perimeter drain	31.8	8,564	12,718	5,003	56	668	69

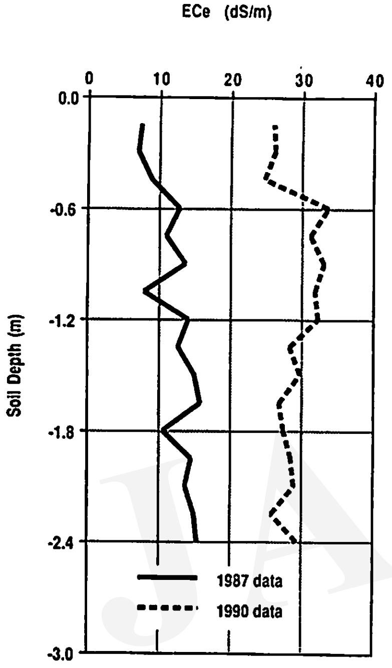

Fig. 3. Electrical conductivity of soil saturation extract (ECe) in location AB2 in 1987 and 1990.

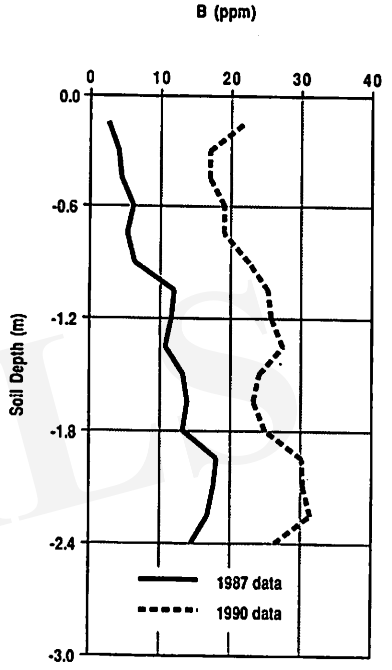

Fig. 4. Boron (B) concentration of soil saturation extract in location AB2 in 1987 and 1990.

electromagnetic device. Most of the observations were made between the fall of 1987 and the summer of 1990.

3. Results

The four-year (1986–90) average annual precipitation was 187 mm, and the reference evapotranspiration (ETo) was 1,535 mm. The estimated crop coefficient in 1990 was about 0.8 when the root zone was highly salinized which is well below the usual crop coefficient of 1.25 for trees grown under nonsaline conditions. The total irrigation applied in 1990 was 1,050 mm while previous irrigations were much lower, 370 to 530 mm. The water table prior to 1987 was about 0.6 m beneath the soil surface and has since been gradually lowered to 1.8 to 2.3 m soil depth from root water extraction between 1988 and 1990.

Table 1 presents chemical analyses of the irrigation and subsurface (tile) drainage waters for the 1990 irrigation season. The drainage waters from croplands used as irrigation for the trees had an average electrical conductivity (EC) of 10 dS/m (dominated by Na, SO_4 and Cl ions), an average sodium adsorption ratio (SAR) of 11, and average boron (B) and selenium (Se) concentrations of 12 mg/L (ppm) and 396 ug/L(ppb), respectively. The subsurface drainage from the eucalyptus plantation had an average EC 3.2 times greater than the irrigation water, SAR 6.3 times greater, B 4.2 times

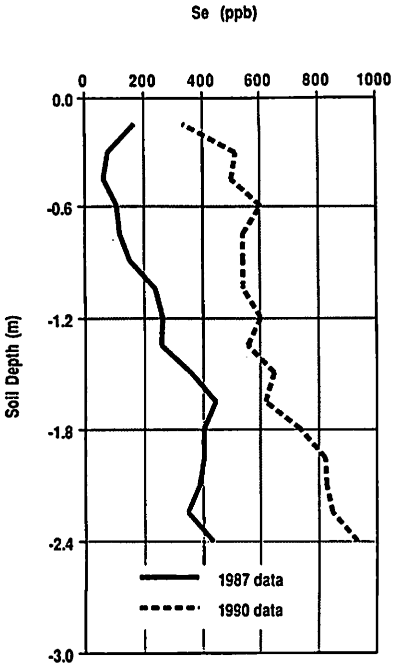

Fig. 5. Selenium (Se) concentration in soil saturation extract in location AB2 in 1987 and 1990.

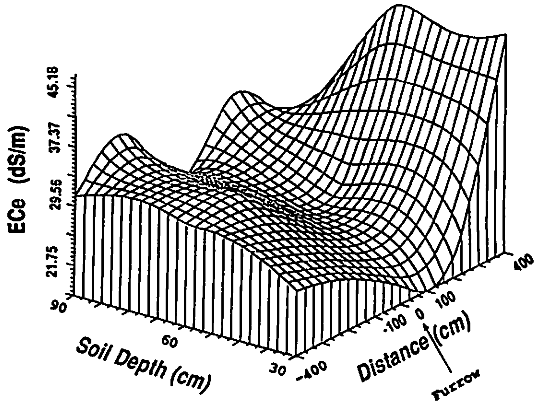

Fig. 6. Transverse (across furrow) and vertical ECa, measured with a salinity probe on August 17, 1990, two days after irrigation at location AB2.

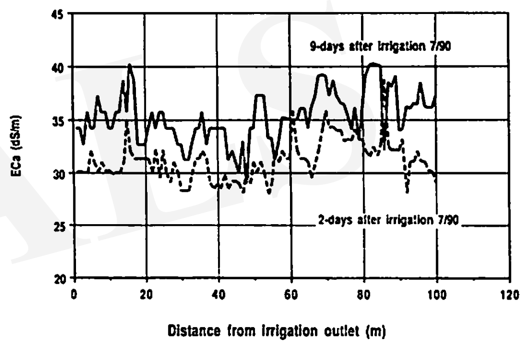

Fig. 7. Longitudinal (along furrow) ECa in surface soil depth, measured with a EM-38 device, two and nine days after irrigation in block 4 in July 1990.

greater, and Se 1.8 times greater. The tile effluents from the Atriplex and perimeter drains were similar to the effluents from the trees indicating that the effects of imposed irrigation treatments are not yet fully apparent in the tree drainage waters. The residual drain waters collected in the evaporation tanks had ECs ranging from 39 to 166 dS/m while undergoing desiccation and precipitating out evaporite minerals such as thenardite (Na_2SO_4), bloedite ($Na_2SO_4 \cdot MgSO_4 \cdot 5H_2O$), and burkeite ($Na_2CO_3 \cdot 2Na_2SO_4$).

Figures 3, 4 and 5 show respectively the EC, B and Se concentration levels in the root zone at monitoring station AB2 (Fig.2) for 1987 and 1990. Significant increase in salinity and trace element contents are noted. The SAR in the surface 0.3 m soil depth also increased from 15 to 26 between 1987 and 1990. The estimated leaching fraction (LF) for the 1990 irrigation season was 0.16. LF is defined as the ratio of drain water to applied water. The trees showed symptoms of lower leaf tip burns and reduced vigor in growth. Apparently, this LF of 0.16 may have been too low to control salinity and B in the root zone to levels tolerable to the trees.

Figure 6 shows the across-the-furrow and vertical EC, measured by an Martek salinity probe, two days after irrigation on August 17, 1990 at station AB2. Fig. 7 shows the longitudinal EC in the soil surface, measured by a Geonic EM (electromagnetic) 38 probe, two and nine days after irrigation in Block B4 (Fig. 2) in July 1990. 7/90 and 9/24/90. Both Fig. 6 and 7 indicate the extent of spatial variability in soil salinity in the tree plantation, and Fig. 7, the extent of temporal changes in soil salinity.

Figure 8 presents volumetric soil water contents at station AB2. Irrigation was applied on

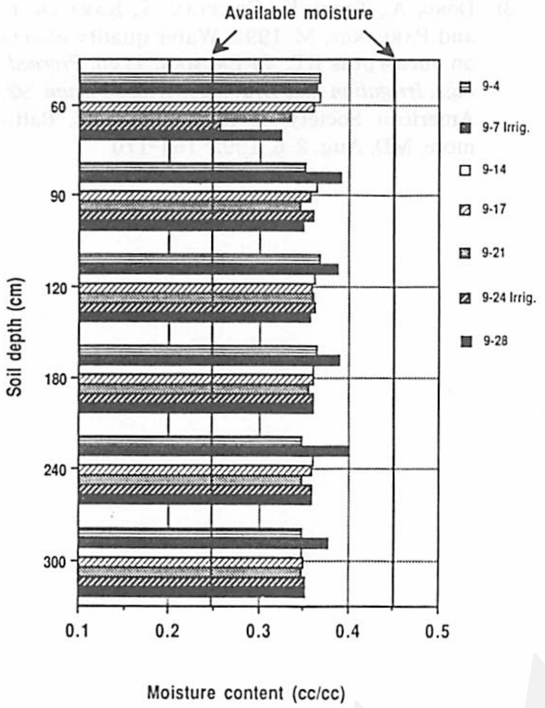

Fig. 8. Volumetric soil water contents during September 1990 at location AB2.

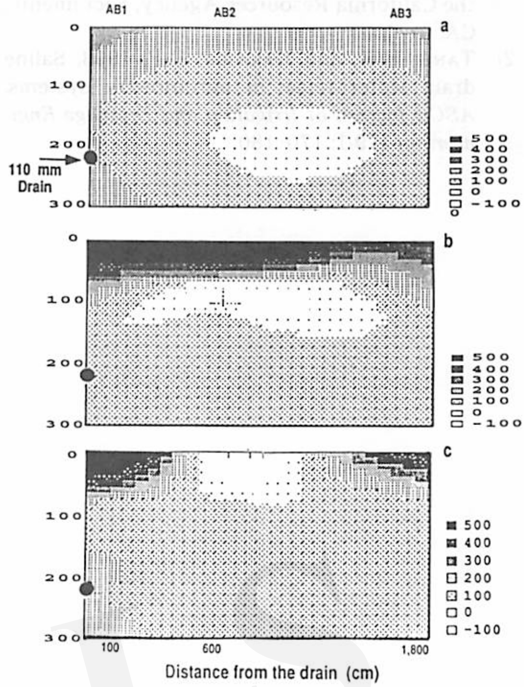

Fig. 9. Soil water pressure head (in cm) at location AB in September 1990: (a) before irrigation, (b) one day after irrigation, and (c), nine days after irrigation.

9/7/90 and 9/24/90. This figure shows that soil moisture did not change appreciably prior to and after irrigation. It appears that the soil salinity had built up to such a high level (Fig. 3) that the trees were unable to fully extract the available soil water. This is partially confirmed by visual leaf toxicity symptoms and lack of vigor in growth. The results of piezometer tests indicate no seepage across the impermeable clay layer between the 3.6 and 4.6 m depths.

Figure 9 plots the total hydraulic head away from the relief drain (closed circle at the 2.3 m depth) at station AB before irrigation and one and nine days after irrigation in September 1990. The equipotential zones show water flow directions from darker to lighter stippling.

4. Summary

An experimental eucalyptus tree plantation was successful in lowering the shallow ground waters and in using saline subsurface drainage waters from a nearby cropland. But after several years of irrigation, a substantial buildup of salinity, boron, and selenium occurred throu-gh-out the root zone. The 1990 data on soil water contents indicate that the trees are unable to fully extract the available soil water to meet their ET needs. The elevated levels of EC and B were approaching levels that would have deleterious impacts on the performance of the eucalyptus trees. The SAR in the surface soil has risen to levels high enough to reduce water infiltration rates. To sustain this agroforestry system over the long term, there is a need to increase the leaching fraction to about 0.2 to prevent further build up on salinity and boron. There is a need to closely monitor the soil profile so that the trees can survive and continue to consume excess drainage waters.

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Water Resources from Iceberg of Antarctica and Undersea Reservoir

Hiroshi KOKUBU*

1. Introduction

Icebergs have long been considered a water resource to an arid area. The first specific idea was to pull an iceberg from Antarctica to Australia and other southern hemisphere. Actual towing of an iceberg to Saudi Arabia was tried in the latter part of the 1970's. But there were many difficulties: melting and collapsing of the iceberg during its' transport. There are also problems to land an iceberg whose draft is deeper than shore depth. Undersea reservoir is being investigated and developed in Okinawa, Japan because of a shortage of water. This new system has an adequate equipment for iceberg transportation to protect pure water against mixing with salt water and suppling pure water to the land.

This paper describes the feasibilities of actual use of an iceberg as water resources by developing undersea reservoirs.

2. Iceberg

Salt water forms almost all of the contents of water on the earth. This means that pure water is scarce. Table 1 shows a list of waters. We see that the volume of ice in Antarctica is so big that there exists almost the entire pure water resources on this vast continent. On the cold areas, like Antarctica or on high mountains, the snow falls repeatedly without melting, consolidating in layers. After a long period, the snow forms ice. Ice moves if it lies on the slope. This is called a glacier. The ice on the flat area, for example, in Antarctica or Greenland, does not move. We call this an ice sheet. The biggest thickness of ice sheet on the Antarctic continent is more than 4,000 meters.[1] Around the ice sheet, there is movement of ice to the lowest point and finally to the sea. This is the birth of iceberg. The big birth places of icebergs are on the Ross Ice Shelf, the Ronne Ice Shelf and the Amery Ice Shelf (See Fig. 1).

The produced quantity of icebergs in one year is only 0.005% of all ice on Antarctica, but this quantity is more than one trillion tons.[4] This enormous volume of iceberg would be melted and vanished after one to ten years.

3. History

The origin of the idea to use an iceberg as a water resource is not clear. The modern idea was proposed by J. D. ISAACS. His idea was to tow icebergs from Antarctica to southern California. According to his calculations, about one year would be needed to tow an iceberg of the dimensions 16,000×800×200 meters, and as it melt about half of the iceberg or 1.1 billion tons of pure water would remain.[4]

The first published papers about this subject were the study of WEEKS and CAMPBELL (1973) and of Hult and OSTRANDER (1973). The former two scientists mentioned the possibility of towing an iceberg by a strong tugboat from Antarctica to Australia or other countries in the southern hemisphere. For example, towing an iceberg, dimensions of 2,700×2,700×250 meters, at half a knot from Amery Ice Shelf to Western Australia needs about eight months, resulting in 800 million tons of pure water which represents half of the original iceberg.[5,6]

On the other hand, Hult and Ostrander examined the transportation of an Antarctic iceberg by train to southern California.

Prince Mohammed al Faisal al Saud was interested in iceberg transportation for the water supply of Saudi Arabia that he supported two conferences of International Glaciological Society on iceberg utilization. The first conference

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Table 1. Contents of water.[2,3]

(unit: km³)

	Löf (1960)	Nace (1964)	Kayane	%
Salt water				
ocean	1,307,409,000	1,320,000,000	1,349,929,000	97.50
lake		104,000	94,000	0.007
Fresh water				
ice	30,427,500	29,158,500	24,230,000	1.75
Antarctica				1.57
Greenland				0.16
others				0.02
lake	124,600	125,000	125,000	0.009
river	1,150	1,250	1,200	0.0001
soil water	25,160	66,650	25,000	0.002
ground water				0.72
shallow	4,500,000	4,165,000	4,500,000	
deap	5,630,000	4,165,500	5,600,000	
Vapor	14,200	12,900	12,600	0.001
Total			1,384,516,000	100

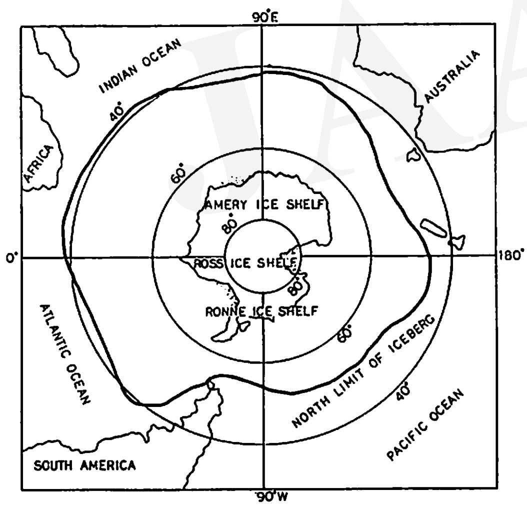

Fig. 1. Antarctica and north limit of iceberg.[4]

took place in Paris in the spring of 1977 and the second occurred the following fall at Iowa State University. Many scientists and engineers discussed the iceberg utilization, and they emphasized the importance of knowing real conditions on real icebergs adrift on the high seas.[7]

"International Iceberg Transportation Company," which is a joint corporation of CICERO of France and Saudi Arabia, was established on October, 1977. The purpose was to create an iceberg business as a water resource by towing icebergs from Antarctica to Saudi Arabia. However, this company became bankrupt after one year. The reason was not revealed, but it was supposed that the towing was so difficult on the high seas by separation or collapse due to cracks or crevasses in the iceberg. In addition, the technical study of an protective cover against melting was not sufficient.[8] We have not heard of any successful real iceberg transportation.

4. Problems

There are many difficult problems to master on the subject. First, as I mentioned above, there are cracks in the iceberg causing it to collapse during transportation on the high seas. This requires the towing speed to be slow. Second, how can we protect an iceberg from melting or mixing with sea water effectively, efficiently and economically? Some people favor the use of protective fabrics or foamed insulation. It must be remembered that both the sides and the bottom of the iceberg need protection. If effective protection is impossible, towing to the northern hemisphere is also im-

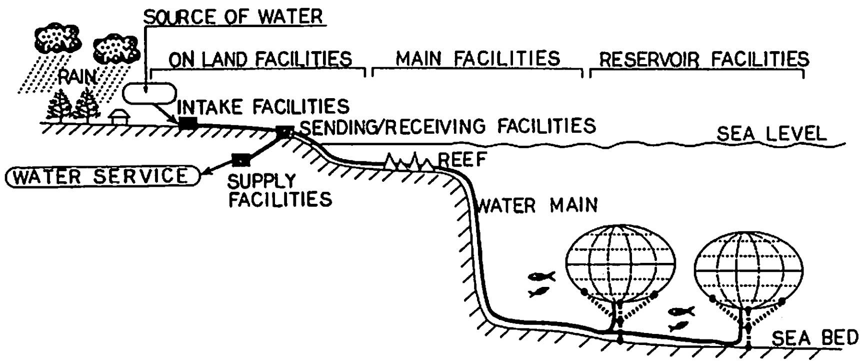

Fig. 2. Constitution of undersea reservoir system.[9]

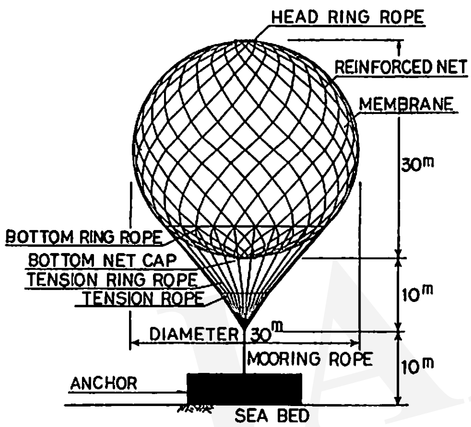

Fig. 3. Sturucture of undersea reservoir.[9]

possible. Third, even if towing is successful, the iceberg will not be able to reach the port because of its big draft. The iceberg must be stopped at a long distance off the coast. The processing from ice to water is a big problem. We know that even a low density ice is not easy to blast or cut, and the processing cost is expensive.[7]

5. Undersea Reservoir

Undersea reservoir is a new water reserve system which is being developed in Okinawa, Japan. Even though the annual precipitation in this province is more than 2,000m/m per year, Okinawa has a social problem of shortage of water almost each year. This is because of its slender shape, short rivers and the rain water flows into the sea rapidly without any reservoir system. There are some dams to stock water, but those are not sufficient to support a population of more than one million. More construction of dams is impossible because of narrow land space and environmental restrictions. Excessive rain water would flow into the sea without utilization, but if it was possible to separate this water from sea water and store it in the sea, we could supply it as a water resource later. This is the basic conception of undersea reservoir. Fig. 2 shows the constitution of this system. It is made up of the following three facilities:

1. ON LAND FACILITIES

   These facilities consist of three facilities; intake, sending/receiving, and supply facilities. Rain water, underground water and river water should be gathered into the intake facilities.

2. MAIN FACILITIES

   Water main is considered to be one steel pipe of 300 mm diameter and branch pipes are flexible of 150 mm diameter.

3. RESERVIOR FACILITIES

   Reservoir is sphere shaped and its membrane material would be ethylene propylene rubber with nylon or polyester, covered with reinforced net and moored with an anchor. The average size of this is shown in Fig. 3. This is installed at the depth of 50 meters to 100 meters undersea as not to block marine passage.

This system is called "MANBO (SUNFISH) PROJECT" because of its similarity to a sunfish wafting in the sea. On land facilities are so small that reserving water in the sea is good effective use of land, and also for the natural

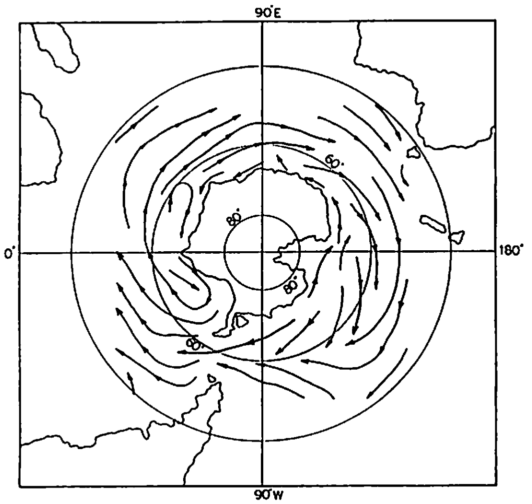

Fig. 4. Antarctic ocean current.[10,11]

environment.

6. Feasibilities

In this subject, our purpose is not towing an iceberg intact, but getting water resources from iceberg to an arid land or desert area. We should not worry about the melting of an iceberg. It is quite natural that ice melts if the sorrounding temperature is over the freezing point. Towing icebergs to Saudi Arabia or some other northern hemisphere without any protection is impossible. Almost all of the specialists don't believe that the perfect protection for melting could be developed. Should we give up the idea of towing an iceberg to a northern hemisphere site? How about to Australia or South America? As I mentioned in HISTORY, according to the calculations of Weeks and Campbell, about half the volume of an original iceberg could be expected to remain when it reached Australia. Other studies show almost the same result as Weeks and Campbell, so towing to a relatively near site from Antarctica without any protective cover has some possibilities. The most difficult problem is to land an iceberg as a water resource. Some scientists suggest the cutting, slicing or blasting of an iceberg near the landing site. But no one has described the specific details of the method, and no one has mentioned how we can protect the melted water from mixing with salt water when we process the ice to water. To solve the above mentioned problems, one huge undersea reservoir system should be considered. If we could wrap an iceberg entirely, we need not worry about its melting, and we will not land a big draft iceberg. After the wrapped iceberg melts, we can adapt it to an undersea reservoir system, and we can supply fresh water to the arid land. Even if the iceberg was not melted entirely, we can assume it as a floating reservoir by mooring it like a ship. We still have a big problem of collapsing, which causes towing difficulty. How could we overcome it? The most important thing is the selection of an iceberg. The following are points to select:

1. Shape must be stable and table shaped.
2. Crevasses must be small and few.
3. Size must not be big.

To chose an adequate iceberg to tow, we should research icebergs between 60 to 50 degrees southern latitude. Fig. 1 shows the northern limit of iceberg. The limit in the Indian Ocean is about 40 degrees southern latitude. The smaller the degree, the fewer the iceberg. The larger the degree, the more crevasses. Once the iceberg collapses it has fewer crevasses. Supposing towing an iceberg to Western Australia, the South Indian Ocean area is the best selection. Fig. 4 shows the current arround Antarctica. We can harness the natural energy to tow iceberg because the major factors of iceberg drift are wind and current.

7. Conclusions

Wrapped iceberg (or water)would be possibly towed because the transportation of water wrapped with Vienna-sausage-shaped cover on the sea had been done in Norway. Undersea reservoir system is now being developed. We can expect this system to be a new and useful facility for water resources from icebergs. The easiest arid site of this subject would be Australia. The first trial should be done at the easiest area. If we succeed, we could expect actual transportation to Saudi Arabia, California or some other northern hemisphere arid sites. Our idea must not be a pipe dream, but a pipeline. A pipeline of water not in our dreams, not in our hopes, but in our homes.

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私共は，今日まで頂いたご支援を基礎として，これからも学会活動を発展させ，御厚志に報いたいと考えております．

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