Journal of Arid Environments (2003) **53**: 61–71
doi:10.1006/jare.2002.1021, available online at http://www.idealibrary.com on IDEAL®

The role of overland flow in sediment and nitrogen budgets of mesquite dunefields, southern New Mexico

Anthony J. Parsons★*, John Wainwright†, William H. Schlesinger‡, Athol D. Abrahams§

★*Department of Geography, University of Leicester, University Road, Leicester LE1 7RH, U.K.*
†*Department of Geography, King's College London, Strand, London WC2R 2LS, U.K.*
‡*Nicholas School of the Environment and Earth Sciences, Duke University, Durham, NC 27708, U.S.A.*
§*Department of Geography, State University of New York at Buffalo, Buffalo, NY 14261, U.S.A.*

(Received 5 November 2001, accepted 18 March 2002)

Rainfall-simulation experiments were conducted within the Jornada Experimental Range, southern New Mexico, on small plots located on mesquite nabkha and interdune spaces. Data from these experiments were used to determine runoff, sediment and nitrogen losses, and to measure the effect of soil crusts in interdune spaces on these quantities. Results show that runoff from the nabkha plots amounted to only 7·8% of the applied rainfall, whereas from the interdune plots it was 75·7%, rising to 90·8% from plots where the soil crust was protected from raindrop impact. Sediment yield from the nabkha plots averaged $0{\cdot}24\,g\,m^{-2}\,s^{-1}$ and from the interdune plots it averaged $0{\cdot}70\,g\,m^{-2}\,s^{-1}$, with no difference between the protected and unprotected plots. Nitrogen losses in runoff averaged $1{\cdot}45\,mg\,l^{-1}$ from the nabkha plots and $0{\cdot}61\,mg\,l^{-1}$ from the interdune plots. However, because of the much greater runoff from the interdune areas total nitrogen loss from interdune plots was three times that from the nabkha plots. Rates of annual sediment loss by runoff are estimated to be similar to rates of aeolian erosion, but rates of dissolved nitrogen loss are estimated at only between 2% and 7% of total atmospheric deposition and less than 1% of nitrogen fixation by mesquite.

Keywords: runoff; sediment budgets; nitrogen budgets; mesquite nabkha; Chihuahuan Desert

*Corresponding author. Fax: +44-116-252-3854. E-mail: ajp16@leicester.ac.uk

0140-1963/03/010061 + 11 $35.00/0

Introduction

The formation of mesquite nabkhas is an important component of the desertification of semi-arid grasslands in many areas of the south-western United States (Gile, 1966; Grover & Musick, 1990; Langford, 2000). Typically, nabkhas are convex mounds of sand up to 2 m in height and several metres in diameter, encasing mesquite shrubs. Nabkhas are separated by interdune spaces, likewise several metres across. The dunes may be aligned in 'streets' (Okin & Gillette, 2001) parallel to the dominant wind direction. Because of the increase in land area covered by mesquite nabkha fields during the past century (e.g. Buffington & Herbel, 1965), this vegetation community is now a major influence on the water, sediment and nutrient budgets of large parts of the arid south-western United States.

Previous research into the sediment and nutrient budgets of mesquite nabkha fields has concentrated on aeolian processes. Hennessy *et al.* (1985), for example, argued that the establishment of mesquite allows wind erosion of the interdune area and a deposited dune soil. Likewise, Gile (1966) argued that interdune deflation was the major source of sand for the dunes in the Mesilla Basin of southern New Mexico. Langford (2000), working in the same area, confirmed that interdune areas are a major source of nabkha sand, but also showed that sand transported 1–2 km was also a significant component of both nabkha and interdune sand. However, if aeolian processes are solely responsible for the formation of nabkhas, then they will grow in height until limited by erosion in the interdune area, or nabkhas themselves reach a height above which wind velocity is sufficient to re-entrain the sand (Cooke *et al.*, 1993). Although the coarse texture of nabkha soils indicates that they are formed from saltating sand particles (Gile *et al.*, 1981), they also accumulate suspended particles, organic matter and associated nutrients as well as nutrients in rain funnelled into the soil along plant stems (Whitford *et al.*, 1997). At the same time as being sites of aeolian deposition of both sediments and nutrients, nabkhas and their associated interdune spaces are also sources of aeolian silt and clay, and associated nutrients. Estimates (Gillette & Monger, 2002) of soil-loss rate ($1400\,g\,m^{-2}\,a^{-1}$) for mesquite nabkha fields in the Jornada Basin in southern New Mexico show this rate to be much greater than the average rate of dust deposition ($19{\cdot}4\,g\,m^{-2}\,a^{-1}$), indicating that aeolian processes lead to substantial loss of nitrogen from mesquite nabkha fields.

In nabkha regions in Mali, Nickling & Wolfe (1994) noted evidence for runoff processes in interdune areas (micro-drainage channels and surface crusting) indicating that aeolian processes are not operating alone in this environment. Similar soil crusting and drainage channels can be seen in the interdune areas between the nabkhas of southern New Mexico, raising the question of the importance of runoff processes to their establishment and maintenance. However, although soil crusts reduce infiltration, they are also fragile. They are easily broken, for example, by animal activity (Neave & Abrahams, 2001) and by high-intensity rainfall (Kidron, 2001), so that their effectiveness in promoting runoff may not be as great as their extensive presence may suggest.

The aim of this study is to investigate the role of runoff processes in the nutrient and sediment budgets of mesquite nabkha fields. Because the generation of surface runoff is significantly affected by the presence of soil crusts, we also investigate the stability of these crusts during high-intensity rainstorms and examine the effects of these crusts in promoting water, nitrogen and sediment transport.

Study area and methods

The study was undertaken at the Jornada Experimental Range, 40 km north-east of Las Cruces in Doña Ana County, New Mexico, as part of the Jornada Basin

Long-Term Ecological Research Program. Mean annual precipitation at the study site is 230 mm, of which about 60% is derived from high-intensity summer thunderstorms that generate almost all of the surface runoff.

Rainfall-simulation experiments were conducted on small plots, using a rainfall simulator, similar in type to that described by Luk *et al.* (1986). The simulator had a design rainfall intensity of $144\,mm\,h^{-1}$, median drop size of 2·40 mm, and kinetic energy of $1{\cdot}04\,J\,m^{-2}\,s^{-1}$, at the ground surface. In the interdune areas, experiments were conducted on eight pairs of plots ranging in gradient from 3·75° to 8°. Each plot was 1 m × 1 m, bounded on three sides by 15-cm-high metal sheeting pushed carefully about 5 cm into the soil. To prevent unnaturally high infiltration on the plots due to the insertion of the sheeting, fine sediment was tamped around the inside of the plot boundaries and then sealed by pouring a mixture of wood glue and water onto this sediment. On the outside of the plots, sediment was banked up against the boundaries and a shallow trench was dug around the plot. Because rain from the simulator fell both within and outwith the plot, there was no danger of lateral seepage of infiltrated water out of the plot and the shallow trench prevented ingress to the plot of runoff occurring around it. On the fourth (downslope) side, each plot was bounded by a steel lip, sealed into the plot surface in the same manner as the bounding walls. Runoff water escaped from the plot over this lip into a PVC gutter. Discharge from the gutter was collected over 15-s intervals throughout the experiments, which typically lasted for 15 min. For approximately the first 5 min of each experiment sampling was initiated every 30 s, thereafter every minute. Rain gauges were placed at the corners of each plot to measure actual rainfall during each experiment and, for some plots, a plastic bottle was placed adjacent to one of the gauges to collect a sample of the simulated rainfall. A 1-mm mesh screen rested on the top of the bounding metal sheeting of one plot of each pair to absorb the kinetic energy of the falling rain.

On the mesquite nabkhas, similar experiments were performed on six individual plots ranging in average gradient from 13·9° to 20·8°. These plots were 1-m wide and extended from the dune crest down to the edge of the plant canopy. Their lengths varied from 2·5 to 4 m. Rain falling onto these plots was measured using six rain gauges, placed at the corners and midway along the sides of the plots, and a plastic bottle was placed adjacent to one of the gauges to collect a sample of the rainfall on three of the plots. Because of the low runoff amounts from some of these plots, runoff sampling times were often extended from 15 s to a maximum of 60 s.

After the experiments, runoff samples were taken to the laboratory where they were weighed, and subsamples of the runoff water were filtered through pre-rinsed 0·45-μm GA-6 Metrical filters. Similar subsamples were taken from the samples of the applied rainfall. The runoff samples were left for 24 h, then decanted, dried at 105°C and then reweighed to determine sediment load. Because sediment loads in some samples were very high, runoff weight was determined by subtracting the sediment weight from the total sample weight. Runoff volume was calculated by assuming a water density of $1\,Mg\,m^{-3}$. The water subsamples were subsequently analysed for NH_4, and NO_3 using standard methods on a Traacs 800 Autoanalyzer. Total inorganic N is taken as the sum of NH_4-N and NO_3-N. Each subsample was then subjected to persulphate digestion and reanalysed. The difference between the digested and undigested concentrations is assumed to represent the dissolved organic nitrogen.

Results

Runoff

For the interdune plots, runoff from the mesh-covered plots averaged 90·8% of the applied rainfall, whereas for the uncovered plots it averaged 75·7%. In all eight pairs, the runoff from the covered plot was greater than for the uncovered plots, indicating that raindrop impact energy on unprotected surfaces is sufficient to damage the soil crust and increase infiltration, as noted by Kidron (2001). Final runoff rates for the covered and uncovered plots also show the former to be greater than the latter in all eight pairs. Furthermore, whereas the total runoff from the covered plots was 1·20 times that from the uncovered plots, the ratio of final runoff was 1:1·24, suggesting that the break-up of the crust is a progressive process throughout the storm event and that the fragile soil crust is destroyed during high-intensity rainfall. On the interdune plots, runoff began within a minute of starting the experiments and typically approached equilibrium within 3–4 min (Fig. 1(a)).

In comparison, for the plots on the nabkhas the runoff averaged only 7·8% of the applied rainfall and final runoff rates averaged only 10·6%. Runoff did not commence until a few minutes after the start of the experiments (average 3·3 min) and typically increased thereafter, with no indication of equilibrium being reached within the duration of the experiments (Fig. 1(b)).

Sediment yield

In contrast to the significant difference in runoff between the covered and uncovered plots, the difference in sediment yield was negligible. Average sediment yield was 0·69 $g\,s^{-1}$ from the uncovered plots and 0·71 $g\,s^{-1}$ from the covered plots. However,

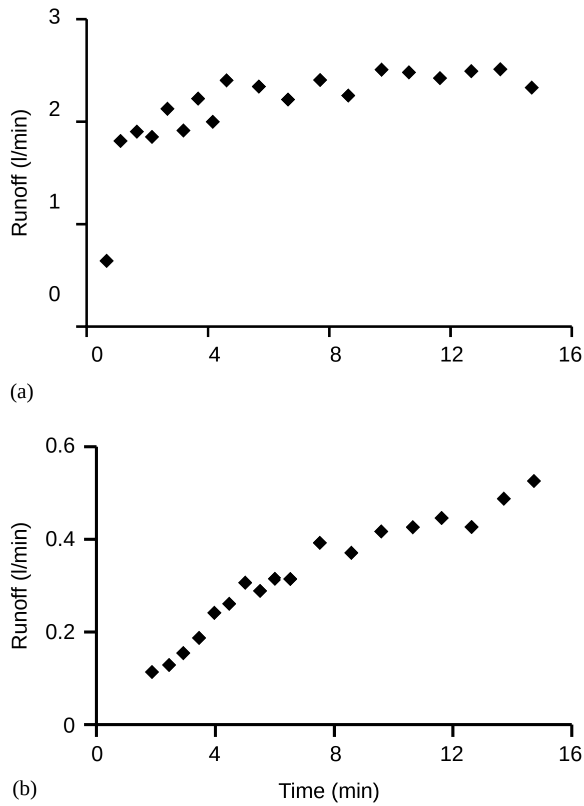

Figure 1. Example hydrographs from rainfall simulation plots: (a) interdune plot, and (b) nabkha plot.

for five of the eight pairs the sediment from the uncovered plot was greater than that from the covered one. If there is any surprise in this result, it is that the sediment yield from the uncovered plots was not greater than that from the covered ones. Given that detachment is due to raindrop impact, the lesser impact on the covered plots might be expected to result in significantly reduced sediment detachment and hence reduced sediment yield. Furthermore, the greater resistance to erosion of the crusted surface (Kidron, 2001) and the lesser break-up of the crust on the covered plots might also be expected to reduce sediment yield from these plots. That this was not the case, suggests that the lower detachment rate on the covered plots was largely compensated by the higher runoff rate. Thus, while the presence and break-up of the crust is significant for runoff, it seems not to affect sediment yield. The implication is that the greater runoff on crusted surfaces is balanced out by the greater sediment availability on uncrusted surfaces.

Similarly, in contrast to the near ten-fold difference in runoff between the nabkha and interdune plots, there was only a near three-fold difference in sediment yield: $0{\cdot}24\,g\,m^{-2}\,s^{-1}$ and $0{\cdot}70\,g\,m^{-2}\,s^{-1}$, respectively, for the nabkha and interdune plots, despite the effect that the greater length of the nabkha plots might be expected to have (Parsons *et al.*, 2002). The small difference is most likely to be due to the difference in steepness of the plots and the mechanisms of sediment entrainment. In contrast to the interdune plots, where sediment was entrained mainly by raindrop impact and transported off the plots in the runoff, on the nabkhas much of the sediment was mobilized as small debris flows that periodically delivered slugs of sediment to the gutter. These debris flows were a consequence of the steep slopes of these plots (average 16° compared to 6° on the interdune plots) and the ample supply of loose sand.

For both the nabkha and the interdune plots, the temporal changes in sediment yield closely matched those in runoff. Thus, for the interdune plots sediment flux reached a maximum soon after the beginning of the experiments. In some instances, there was an indication of an exhaustion effect as sediment flux declined towards the end of the experiment, as is illustrated in Fig. 2(a). For the nabkha plots, sediment flux typically increased throughout the experiments (Fig. 2(b)), as did the runoff. Consequently, both in the interdune areas and on the nabkhas sediment concentration remained fairly constant throughout the experiments (Fig. 3).

Sediment concentrations on the interdune plots averaged $20\,g\,l^{-1}$, whereas on the nabkha plots they averaged $186\,g\,l^{-1}$. The high sediment concentration in runoff from the dune plots accords with comparably high values reported elsewhere in runoff from dunes (Rutin, 1983; Kidron & Yair, 2001) where they have been attributed to high sediment availability and to the low cohesiveness, and consequently low resistance to raindrop energy, of sand. These factors may well contribute in the present case, though the observed debris flows on the nabkha plots imply that resistance to raindrop energy may be less important than suggested elsewhere. The sediment concentration in runoff from the interdune plots is comparable to that from plots in grassland and creosotebush shrubland within the Jornada Basin (Neave & Abrahams, 2001).

Nitrogen yield

To determine the dissolved nitrogen losses from the plots, quantities in samples of runoff should be corrected by subtracting the nitrogen content of the applied water. Although samples of the applied water were collected from some plots, they were not taken from all. Unfortunately, our results show that the various forms of N in the applied water varied substantially (by almost a factor of ten, in the case of NO_3-N, though by substantially less for NH_4-N and DON). Since our data do not show any trends in N content of the applied water, or any significant differences between N

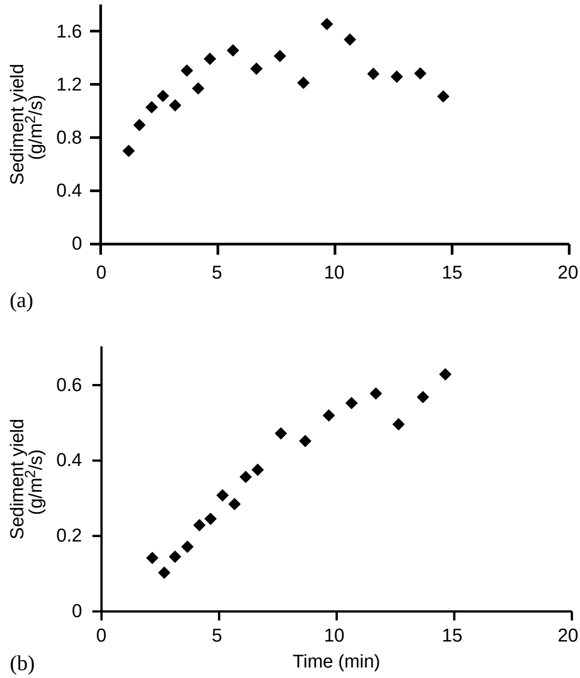

Figure 2. Example sedigraphs from rainfall simulation plots: (a) interdune plot, and (b) nabkha plot.

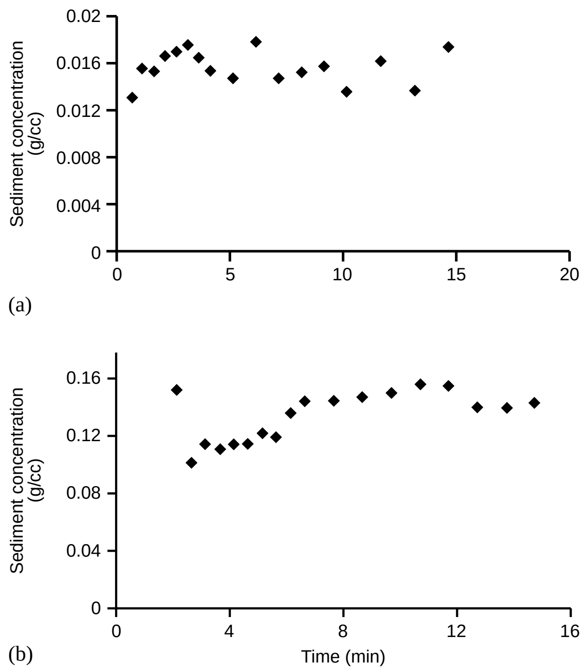

Figure 3. Examples of sediment concentration throughout rainfall simulation experiments: (a) interdune plot, and (b) nabkha plot.

content for the nabkha and interdune plots, to correct the nitrogen losses and report average differences between the runoff samples of the interdune and nabkha plots we have subtracted the average values for all samples of applied water. However, for illustrating trends in nitrogen content in runoff water from individual experiments we have used the uncorrected data.

As may be expected, concentrations of nitrogen in runoff from the nabkha plots were substantially higher than those from the interdune plots. Losses of NO_3-N, NH_4-N and DON from the nabhka and interdune plots were 0·28, 0·28, 0·90 mg l^{-1} and 0·12, 0·02, and 0·47 mg l^{-1}, respectively. These differences may be understood in terms of the lower nitrogen content of the interdune soils (less than half that beneath mesquite canopies: Skujiņš, 1981). However, because of the much lower runoff volumes in the nabkhas, actual losses of dissolved nitrogen were less from the nabkhas than they were from the interdune areas. Multiplying these concentrations by runoff amounts give losses of 0·08, 0·08 and 0·22 mg m^{-2} min^{-1} from the nabkhas but 0·24, 0·06 and 0·87 mg m^{-2} min^{-1} from the interdune areas. As with sediment yield, the differences between nitrogen yield on the covered and uncovered plots was not significant.

Whereas the nabkha plots showed a general decline in concentrations of all forms of nitrogen with time into the experiments (Fig. 4(a)), the decline was much less pronounced for the interdune plots (Fig. 4(b)). Quantitatively, this difference can be

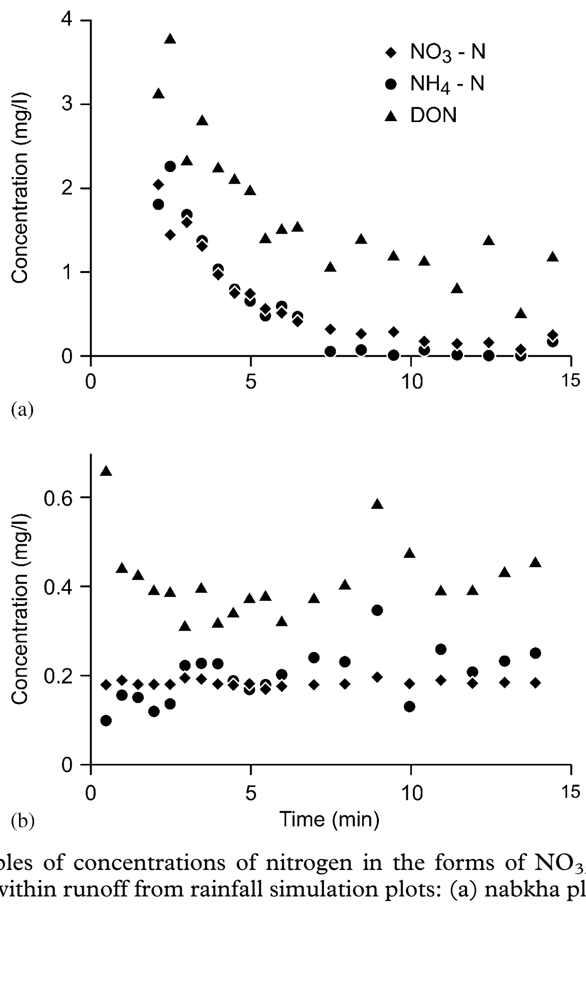

Figure 4. Examples of concentrations of nitrogen in the forms of NO_3, NH_4 and dissolved organic nitrogen within runoff from rainfall simulation plots: (a) nabkha plot, and (b) interdune plot.

expressed by the ratio of concentrations of the different forms of nitrogen in the runoff at the end of the experiments to those at the beginning. For the nabkha plots the ratios of NO_3, NH_4 and DON average 0·29, 0·17 and 0·61, respectively, whereas for the interdune plots the respective ratios are 0·70, 2·02 and 0·79.

Discussion

In order to evaluate the significance of runoff for the movement of sediment and nutrients within mesquite nabkha fields, it is necessary to convert the results from these field experiments into estimates of annual rates using rainfall data, to compare these rates with data on aeolian transport rates and, for the nitrogen losses, with rates of N fixation by the mesquite. Rainfall data suitable for the calculation of annual rates are available from a nearby site within the Jornada Basin for the years 1997–2000.

Sediment yields

Interdune sediment yields

For the interdune areas, sediment yield is a simple function of runoff. Because sediment concentration is fairly uniform for different runoff volumes, we can estimate annual loss of sediment from interdune areas simply as the total rainfall amount in excess of the threshold intensity needed to initiate runoff multiplied by the average sediment concentration ($20\,g\,l^{-1}$). One estimate of this threshold is the average loss to infiltration during the experiments, which was $36{\cdot}67\,mm\,h^{-1}$. This threshold probably gives a minimum estimate of annual runoff because the infiltration rate was determined from a rainfall intensity that is very seldom exceeded in natural rainfall at Jornada, and is one which might be expected to cause an unusually high rate of crust breakdown. Furthermore, it makes no allowance for the relationship between infiltration and rainfall rate (Hawkins, 1982). In contrast to this value, Kidron & Yair (2001) identified a threshold intensity for runoff of $9\,mm\,h^{-1}$ on crusted dune sites in Israel under natural rainfall of relatively low intensity. Taking these two values as the plausible upper and lower limits for the runoff threshold gives an annual sediment yield from the interdune areas of between 368 and $1228\,g\,m^{-2}\,a^{-1}$, based on the measured flux from the 1-m^2 plots used in this study.

Nabkha sediment yields

For the nabkha, sediment mobilization as debris flows depends not only on rainfall intensity but also on rainfall amount. Once the pore spaces within the surface sand have become sufficiently filled with water, debris flows will be initiated. A minimum estimate of the debris flows generated on the nabkhas can be obtained from the estimated exceedence of the runoff threshold observed in the experiments multiplied by the observed sediment concentration. If it is assumed that nabkhas are circular with radius equal to the average length of plots used in the experiments (3·1 m), then this estimate gives an annual sediment yield of 3·29 kg from a nabkha with surface area of $30{\cdot}2\,m^2$, equivalent to delivery of sediment along the nabkha's perimeter of $0{\cdot}2\,kg\,m^{-1}$. However, debris flows can be expected to be initiated at lower intensities than those used in the experiments. To obtain an upper estimate of sediment yield from nabkhas by debris flows, we have used the average total rainfall required in each of our experiments for high concentrations of sediment, resulting from debris flows, to be recorded in the runoff. This calculation yields an estimate of 14·2 mm of rain necessary to initiate debris flows on the nabkhas. Because such rain will initiate debris flows only if the water remains within the surface layer, a threshold for such initiation, based upon infiltration, is necessary. For this threshold, we have used the same value as for the interdune sites. Thus, the minimum conditions for debris flows to be initiated are assumed to be rainfall intensities in excess of $36{\cdot}67\,mm\,h^{-1}$ and during events producing in excess of 14·2 mm rainfall. Events of this magnitude are rare and only two occur in the 4 years of available data. Using these values, together with the observed sediment concentration in runoff yields an estimate of $43{\cdot}68\,kg\,a^{-1}$ from a nabkha with a surface area of $30{\cdot}2\,m^2$, equivalent to $2{\cdot}24\,kg\,m^1$ along its perimeter.

Nitrogen

Interdune nitrogen yields

As with the sediment yields, concentration of forms of dissolved N in runoff from the interdune areas appeared relatively constant throughout the experiments, so that, as with sediment yields, first estimates of nitrogen losses in runoff can be obtained simply as the total rainfall amount in excess of the threshold to initiate runoff multiplied by the dissolved N concentrations of the runoff. Using the same upper and lower thresholds of runoff as for sediment yield gives annual losses of NO_3-N, NH_4-N and DON between 2·28, 0·35, and $8{\cdot}67\,mg\,m^{-2}\,a^{-1}$ and 7·61, 1·17, and $28{\cdot}92\,mg\,m^{-2}\,a^{-1}$, respectively, totalling 0·11 to $0{\cdot}37\,kg\,N\,ha^{-1}\,a^{-1}$.

Nabkha nitrogen yields

In contrast to the sediment delivered from the nabkhas to the interdune spaces, dissolved nitrogen delivery is a function of runoff alone. From the rainfall data, it would appear that dissolved nitrogen losses from the nabkhas are close to zero (0·162, 0·163 and $0{\cdot}526\,mg\,m^{-2}\,a^{-1}$ for NO_3-N, NH_4-N and DON, respectively).

Comparison with aeolian transport and nitrogen fixation rates

Sediment yields

Estimates of sediment yields resulting from rainfall-induced processes are of similar magnitude to the estimates of aeolian soil loss by Gillette & Monger (2002), suggesting that runoff processes are of equal importance to aeolian processes for the sediment budgets of mesquite nabkhas. However, it is important to note that although sediment yields due to rainfall-induced processes have been given in $g\,m^{-2}$ for purposes of comparison with aeolian rates, recognition needs also to be given to travel distances of eroded sediment. Inasmuch as the aeolian rates are based upon measurements of ground lowering, they represent export of sediment from the mesquite dunefields. The same is not true for the sediment loss due to rainfall-induced processes. The debris flows on the nabkhas stop at the edge of the dune mound as the gradient becomes insufficient to maintain the movement. Thus, this process delivers sediment from the dunes into the interdune spaces and probably provides a renewable supply of sediment for aeolian erosion from the interdune spaces and deposition on the dunes. Likewise, the fluxes from the interdune plots are reasonable estimates of sediment delivery to channel networks linking the interdune spaces. These networks are only locally integrated and typically terminate in local topographic lows. These topographic lows will be sinks for runoff-transported sediment but may provide the source for the 1–2 km distant sand identified by Langford (2000).

Nitrogen yields

The estimated rates of total loss of dissolved N by runoff processes are between around 113 and 377 $g\,ha^{-2}\,a^{-1}$ for interdune areas and approximately zero for nabkhas. If we assume that the areas of nabkhas and interdune spaces are approximately equal, the annual loss of nitrogen through runoff processes is between about 2% and 7% of total atmospheric deposition of nitrogen by dryfall and wetfall (Schlesinger *et al.*, 2000), and substantially less than 1% of fixation of atmospheric nitrogen by the mesquite (using the estimates of Rundel *et al.*, 1982 and Johnson & Mayeux, 1990).

Conclusion

Runoff processes play a significant role in the sediment budget of the mesquite dunefields of the Jornada Basin. Movement of sediment by runoff is of similar magnitude to that by wind. Sediment is moved from nabkhas to interdune spaces mainly as debris flows, and then transported by runoff to local topographic lows. This sediment movement provides a mechanism for recycling of sediment deposited by wind on the nabkhas. In contrast, runoff plays a minor role in the movement of dissolved nitrogen in the mesquite dunefields. Most of the runoff is derived from interdune spaces where the nitrogen content of the soil is relatively low. A full analysis of the contribution of runoff to nitrogen movement, however, requires measurement of the nitrogen content of the sediment load, which was not undertaken in this study. Soil crusts in interdune areas enhance runoff, but these crusts are broken up by high-intensity rainfall. In contrast to their effects on runoff, soil crusts have little effect on sediment or nitrogen yields.

This study was funded by the Jornada Long-Term Ecological Research (LTER) program of the National Science Foundation. We are grateful to John Anderson for logistical support and to Kris Havstad of the Agricultural Reseach Service, Las Cruces, for the loan of essential field equipment.

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