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Changes in soil aggregate water stability induced by wetting and drying cycles in non-saturated soil

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Summary

Wetting and drying of remoulded soil resulted in water stable aggregation. The greatest proportions of water stable aggregates arose from wetting and drying in the -1 to -100 kPa range of matric water potential. The effect occurred with sterile and non-sterile soil, but the proportion of water stable aggregates was less with sterile soil.

The application of wetting and drying cycles in the laboratory to non-tilled soil resulted in a steady decrease in the proportion of water stable aggregates. With tilled soil, the proportion of water stable aggregates first increased to a maximum and then decreased steadily with further wetting and drying cycles. However, with sterilized, tilled soil, only a steady decrease in the proportion of water stable aggregates was observed.

Natural water content fluctuations in the field after tillage gave an increase in water stability to a maximum after a few days followed by a steady decrease. The similarity of this result to that obtained in the laboratory for tilled, non-sterilized soil indicates that micro-organisms were probably contributing to the observed short-term changes in the water stability of aggregates in the field.

Introduction

In nature, soil continually undergoes wetting by rainfall, diffusive flow, condensation, etc., and drying by solar radiation, diffusive flow, wind, etc. These cycles of wetting and drying have been related to the formation of soil aggregates in non-aggregated soils. Because of this, some workers (e.g. Telfair *et al.*, 1957; Richardson, 1976) suggested that cycles of wetting and drying can be used to restore some structurally damaged soils.

Wetting and drying has been found to affect the water stability of aggregated soils although the results obtained have been variable. Soulides and Allison (1961) found that wetting and drying cycles decreased the proportion of water stable aggregates >0.5 mm as measured by wet sieving. A decrease in aggregate water stability, as shown by an increase in per cent slaking has also been shown by Tisdall *et al.* (1978). Hofman (1976) obtained a contrary result. He found that the aggregate instability, which was defined as the difference in mm between the average diameters of the aggregates before and after wet sieving, of aggregates sieved immediately after sampling was greater than that obtained when the soil was first air-dried and then rewetted to its original water content or to field capacity.

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Sillanpaa and Webber (1961) found that the end effect of wetting and drying cycles on the water stability of soil aggregates was influenced by the initial aggregate diameter of water stable aggregates produced from aggregates with initial diameters of 2–3 mm, but had no significant effect when the initial diameter was <0.25 mm. Rovira and Greacen (1957) found that one cycle of wetting and drying decreased the water stability of natural soil aggregates, but slightly increased the water stability of soil aggregates formed by simulated tillage.

The effect of tillage on aggregate water stability has received considerable attention. Most of the data available in the literature, however, are for the changes in mean aggregate stability after a number of years of tillage (e.g. Olmstead, 1946; Low, 1972; Tisdall and Oades, 1980). It seems that no attention has been given to aggregate water stability changes in the few days or weeks after tillage. Utomo and Dexter (1981*a*) have shown that tillage increases the amplitude of the water content fluctuations in tilled soil, and it was thought that this change could have a significant effect on aggregate water stability in the period immediately following tillage.

The aim of the work described here is to investigate the effects of wetting and drying cycles on the water stable aggregation of some Red-brown earths. The effect of increased amplitude of wetting and drying on the water stability of soil aggregates produced or disturbed by tillage is also studied, and changes in the period immediately following tillage are considered in detail.

Materials and Methods

Soils

The soils used were the Urrbrae, Strathalbyn and Mortlock fine sandy loams. These soils are Red-brown earths (Stace *et al.*, 1968; Oades *et al.*, 1981), and some properties of these soils are given in Table 1. The Urrbrae and Mortlock soils have only about 5 per cent by weight of primary particles >0.25 mm. The Strathalbyn soil has only about 10 per cent by weight of primary particles >0.5 mm. The water contents given for the various values of matric potentials are not unique values. Thixotropic hardening effects and wetting and drying cycles both influence these values, as does remoulding. The values presented in Table 1 relate only to the drying limbs of the water characteristic curves for field aggregates of these three soils. However, these values are also applied in this paper to remoulded soil samples and to soil samples undergoing wetting. Any results derived from these values (such as the cumulative amounts of wetting and drying of the soil samples in the laboratory experiments reported here) are only approximate estimates and are not to be taken as exact.

Water stable aggregation

Samples from the A horizons of the soils were passed through a 0.25 mm sieve, and were moulded with deionized water at water contents slightly above their plastic limits. After standing overnight, these samples were remoulded for about 2 min. Balls of about 40–50 mm diameter were made by rolling these remoulded soils by hand. The balls were aged for 2 weeks at 20°C and at constant water content, and were then treated as follows.

(a) control: kept at −1 kPa matric water potential on a sintered glass funnel, or

Table 1

Physical properties of the soils

(a) Compositions and Atterberg limits

	Proportion of oven dry soil				
Soil site	*< 20 μm (%)*	*< 2 μm (%)*	*Organic matter (%)*	*Plastic limit (%)*	*Liquid limit (%)*
Urrbrae	49	17	1.7	19.5	26.5
Strathalbyn	36	12	2.8	17.9	30
Mortlock	46	17.5	3.6	23.9	36.5

(b) Gravimetric water contents, w%, at various matric water potentials on the drying limb of the water characteristic of natural surface aggregates

	Matric water potential, kPa				
Soil site	*−1*	*−10*	*−20*	*−100*	*−1000*
Urrbrae	26	22	20	16	10
Strathalbyn	26	21	18	13	11
Mortlock	25	23	22	19	13

(b) subjected to two cycles of wetting and drying between the following matric water potentials: −1 and −10 kPa, −1 and −20 kPa, −1 and −100 kPa, −1 kPa and oven dried (60°C), −10 and −100 kPa, −10 kPa and oven dried (60°C), and −20 kPa and oven dried (60°C).

The 2 weeks of ageing allows the majority of any thixotropic hardening effects to occur (Utomo and Dexter, 1981*b*). It was found that, without this standard ageing period, inconsistent results were obtained and that it was not possible to separate the effects of wetting and drying cycles from the thixotropic effects. These thixotropic effects undoubtedly gave rise to the 'non-microbial changes' observed with soil samples which had been disturbed by freezing and thawing cycles which were discussed by Skinner (1979) in another context. Wetting was done on sintered glass funnels, and drying on sintered glass funnels (−10 and −20 kPa), in a pressure plate apparatus (−100 kPa), and an oven (60°C). One cycle of wetting and drying consisted of wetting, then drying and rewetting. Each additional cycle comprised one additional drying and rewetting. After completion of each wetting and drying programme, all aggregates were air-dried for 10 days. It is assumed that this final air-drying occurred sufficiently slowly so as not to influence the results.

Estimates of the cumulative wetting and drying, $\sum \Delta w$, were made by summing the changes, Δw, in the percentage water contents between the successive water potentials using the values given in Table 1. The final air-drying was not included in $\sum \Delta w$ for the reason given above.

The extent of water stable aggregation within the balls was assessed by wet sieving. The balls were put on a series of sieves (2.0, 1.0, 0.5 and 0.25 mm), then were immersed completely in distilled water to wet-up. Wetting-up was done for 15 min for the Urrbrae and Mortlock soils, and for 30 min for the Strathalbyn soil.

The sieves, with the soil balls on them, were then shaken up and down under water (20 mm amplitude with a frequency of 40 times per min) for 15 min. The aggregates retained on each sieve were oven-dried and weighed. The results are expressed as the proportion of water stable aggregates >0.25 mm diameter. Three measurements were made for each treatment of each soil. Prior to the wetting and drying treatments, no water stable aggregates were present.

Sterilization

In order to assess the influence of soil microbial activity on the water stability of the aggregates the following experiment was done.

A sample of Urrbrae loam was passed through a 0.25 mm sieve. Sub-samples were moulded at a water content slightly above the plastic limit with (a) deionized water, or (b) a solution containing 0.5 mg of NaN_3 and 0.5 mg of $HgCl_2$ per g of soil. The latter was a sterilization treatment used by Tisdall *et al.* (1978), and is not sufficiently concentrated to have any influence on soil flocculation processes. After the soil had stood overnight, it was remoulded, and balls of 40–50 mm diameter were made by rolling this remoulded soil by hand. These balls were pre-aged as described above and were then treated as follows: (a) control: kept at −1 kPa matric water potential; (b) subjected to one, two, four and six cycles of wetting (−1 kPa) and drying (−100 kPa). For the sterilized treatment, the sintered glass funnels and pressure plate were wetted with and connected to reservoirs of the NaN_3 and $HgCl_2$ solutions.

The soil balls were then air-dried for 10 days and the water stable aggregation within the balls was measured by the wet sieving method as described above.

Water stability of field aggregates

Aggregates of 2.0–4.0 mm diameter were collected by dry sieving from tilled and non-tilled plots of the Urrbrae and Strathalbyn soils. Tillage was done with a tined implement to a depth of about 100 mm, and the aggregates were collected immediately after tillage from between the tractor wheel tracks. For the Mortlock soil, aggregates were collected from a non-tilled plot only.

The aggregates were air-dried and were then wetted slowly on sintered glass funnels to a matric potential of −1 kPa by progressively lowering the funnels relative to the free water surface over a period of several days. It was assumed that this air-drying and rewetting were sufficiently slow to have a negligible effect on the results. The water content changes during these two procedures, therefore, were not included in calculations of the estimated cumulative water content changes, $\sum \Delta w$. The aggregates were then treated as follows: (a) control: kept at −1 kPa water potential; (b) subjected to one, two, three, four, six and eight cycles of wetting (−1 kPa) and drying (−100 kPa).

After completion of the wetting and drying cycles, all samples were equilibrated to −1 kPa matric water potential for 2 days, after which their water stabilities were evaluated by the wet sieving method. 20 g of soil from each treatment was put on a series of sieves (2.0, 1.0, 0.5, 0.25 mm) while still at −1 kPa and then immersed in distilled water for 5 min. These sieves, with the aggregates on them, were shaken up and down for 30 min. The aggregates retained on each sieve were oven dried and weighed. The results were expressed as the dry weight proportion of water stable aggregates >0.5 mm diameter. Three measurements were made for each treatment of each soil.

Changes following tillage

The Urrbrae and Strathalbyn soils were tilled in July and September 1979 respectively with a tined cultivator to a depth of about 100 mm. Soil samples of about 5 kg were collected from between the tractor wheel tracks from the 0–50 mm and 50–100 mm layers at various numbers of days after tillage. Aggregates of 1.0–2.0 and 2.0–4.0 mm diameter were separated from these samples by dry sieving. The aggregates were wetted slowly on sintered funnels to a matric water potential of − 1 kPa and then dried to − 10 kPa for 2 days, after which their water stability was determined by the wet sieving method. As before, these slow wetting and dryings were not included in the calculations of $\sum \Delta w$.

Twenty grams of aggregates of each diameter range of each soil were put onto a set of sieves (2.0, 1.0, 0.5 and 0.25 mm for the 2.0–4.0 mm aggregates and 1.0, 0.5 and 0.25 mm for the 1.0–2.0 mm aggregates) while still at − 10 kPa potential, immersed in distilled water for 5 min and then shaken up and down for 15 min. The results were calculated as the proportion of water stable aggregates >0.5 mm.

For the Urrbrae experiment, the changes in aggregate water stability were studied as functions of wetting and drying. This was the natural wetting and drying of soil in the field.

For determination of the cumulative wetting and drying, soil water content was measured each day at 9.00 a.m. (which was taken to be the maximum daily water content as a result of wetting) and at 5.00 p.m. (which was taken to be the minimum daily water content as a result of drying). Soil water content was measured for the 0–50 mm and 50–100 mm layers with five replicates for each treatment at each time of sampling.

The amount of wetting and drying, Δw_i, in any given day, i, was calculated from

$$\Delta w_i = \left| w_{\max(i-1)} - w_{\min(i-1)} \right| + \left| w_{\max(i)} - w_{\min(i-1)} \right| \qquad (1)$$

The cumulative amount of wetting and drying, $\sum \Delta w$, which the soil had undergone between tillage and day j was calculated from

$$\sum_j \Delta w = (\Delta w_1 + \Delta w_2 + \ldots \Delta w_i \ldots \Delta w_j) - j(4\sigma/\sqrt{\pi k}) \qquad (2)$$

The final term is an error term which allows for sampling variation from a random population of top soil water contents. $k = 5$ is the number of replicate samples measured at each time of sampling, and σ is the standard deviation of these water content samples ($\sigma \sim 1$ per cent water content).

For the Strathalbyn experiment because of transportation problems, the cumulative wetting and drying was not determined. In this experiment the change in aggregate water stability was studied as a function of time after tillage.

Results and Discussion

The results in Table 2 show the importance of wetting and drying at the wetter end

Table 2

Effect of two cycles of wetting and drying on the percentage, S, of water stable aggregates >0.25 mm diameter. The approximate cumulative per cent water content change, $\sum \Delta w$, for each treatment is also given

Potentials between which the soil was wetted and dried	*Strathalbyn*		*Mortlock*	
	S	$\sum \Delta w$	S	$\sum \Delta w$
Control (−1 kPa)	9.5	8	6.0	1
−1 and −10 kPa	10.7	28	9.1	10
−1 and −20 kPa	13.4	40	8.9	14
−1 and −100 kPa	16.6	60	18.1	27
−1 kPa and oven dried	15.6	112	16.3	101
−10 and −100 kPa	5.7	35	4.7	19
−10 kPa and oven dried	4.3	87	3.4	93
−20 kPa and oven dried	3.6	73	3.7	89
LSD 5%	3.8		2.7	

of the water potential range (especially between −1 and −10 kPa) on the proportion of water stable aggregates >0.25 mm present (there were no water stable aggregates >2 mm). Also, it can be seen that, when the soil is wetted to −1 kPa and the greater is the cumulative amount of wetting and drying, $\sum \Delta w$, the greater is the proportion of water stable aggregates, *S*. This correlation does not seem to hold for wetting and drying between pairs of different potentials.

Another interesting observation in Table 2 is the significant water stable aggregation which has occurred in the 'control' aggregates. It is probable that this was a consequence of further thixotropic hardening processes which must have occurred during the 1–2 weeks of each wetting and drying experiment. The possibility that such additional thixotropic hardening occurred with the wetted and dried samples cannot be ignored.

These observations of water stable aggregation caused by wetting and drying cycles are consistent with the concept that mechanical stresses are generated within the soil mass by local compaction by effective stresses resulting from interaction between the matric water potential and the soil particles (see Towner and Childs, 1972). It is hypothesized that these effective stresses can generate planes of weakness (microcracks) within the soil mass and that these planes of weakness can provide the initial faces of soil aggregates.

It is reasonable to expect that the greater the changes in water content, the greater are the stresses produced by wetting and drying. As a result, the formation of planes of weakness would be more intensive, with the consequence that the number of aggregates formed would be greater. It has been shown that the rate of breakdown of a soil mass into finer fractions is greater with more rapid wetting (Emerson and Grundy, 1954; Panabokke and Quirk, 1957). Some rates of wetting between different water potentials are shown in Fig. 1. Effects resulting from different wetting rates were not investigated in this work.

It has been suggested that aggregates formed by wetting and drying cycles alone are not stable in water (Baver *et al.*, 1972) and that to obtain water stable aggregates

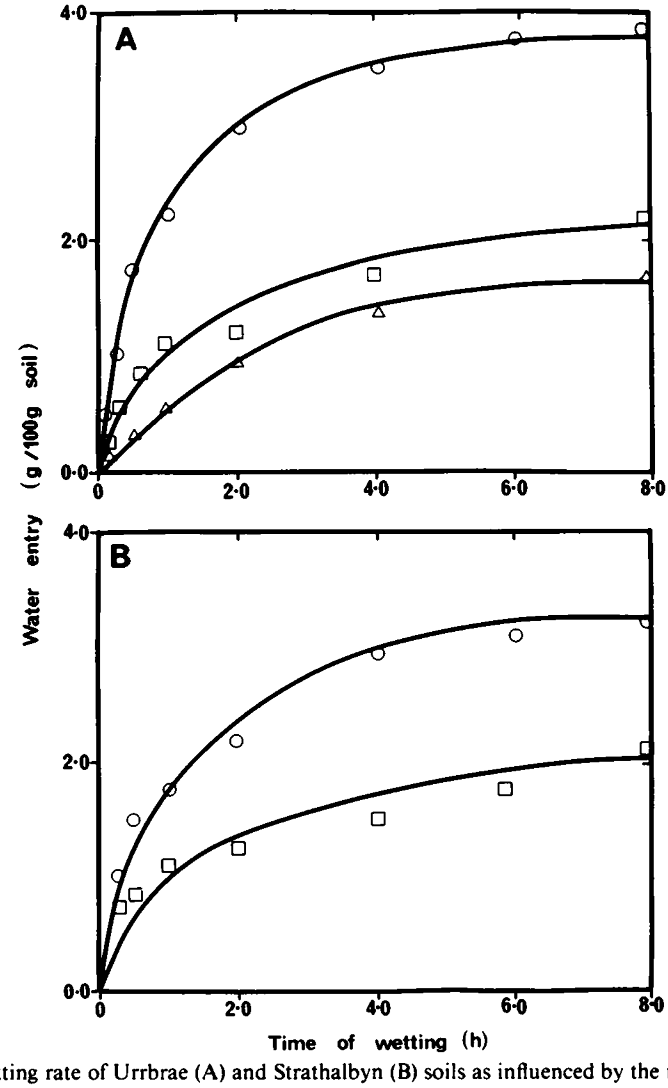

Fig. 1. Wetting rate of Urrbrae (A) and Strathalbyn (B) soils as influenced by the matric water potential from and to which the soil is wetted. ○, −100 to −1 kPa; △, −10 to −1 kPa; □, −100 to −10 kPa.

there must be another process responsible for stabilizing the aggregates involving microbial products or other soil constituents. The importance of soil microbial activity in forming water stable aggregates was assessed by comparing the responses of sterilized and unsterilized soil to wetting and drying cycles.

The results in Fig. 2 show that the percentage of water stable aggregates >0.25 mm increased with increasing numbers of wetting and drying cycles both in sterilized and unsterilized soil. Again, this result supports the proposed mechanism by which wetting and drying cycles cause aggregation. The repeated localized compactive and other stresses during wetting and drying can be expected to result in

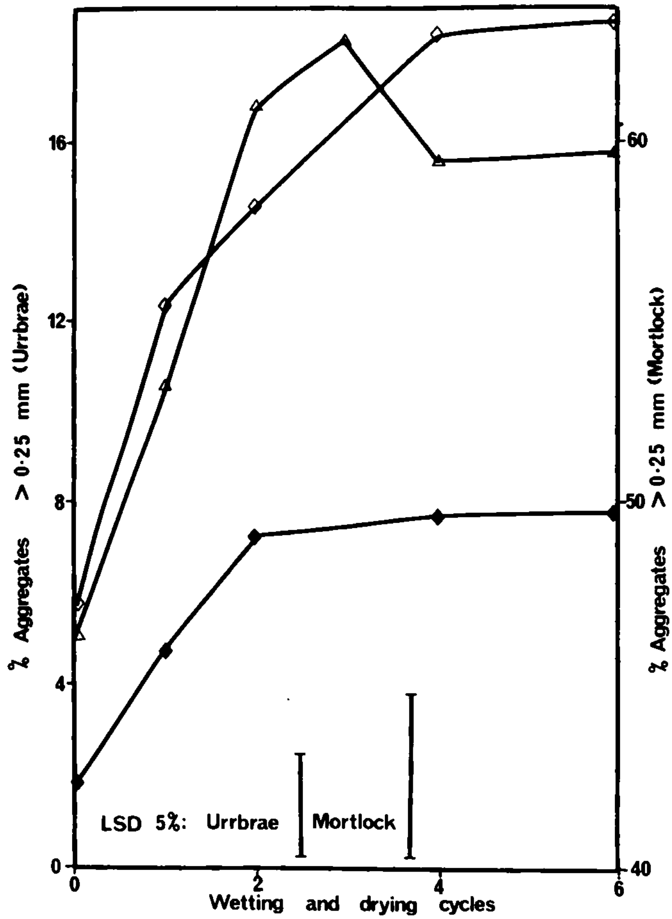

Fig. 2. Effect of wetting and drying cycles on the formation of water stable aggregates of >0.25 mm diameter. For Urrbrae soil the sieving was done for 15 min, and for Mortlock soil it was done for 10 min. ◇, Urrbrae unsterilized; ◆, Urrbrae sterilized; △, Mortlock unsterilized.

more aggregates of greater stability probably up to a maximum value. This result is in good agreement with that of McHenry and Russell (1943) which showed that the percentage of aggregates >0.25 mm increased with increasing numbers of wetting and drying cycles up to 20 cycles and then dropped slightly with further wetting and drying cycles. Woodburn (1944), however, found that the proportion of aggregates of 0.25–2.0 mm diameter increased with up to two cycles of wetting and drying, but then decreased with further cycles. The results in Fig. 2 also demonstrate the importance of soil microbial activity in imparting water stability to aggregates. When microbial activity was prevented by sterilization, wetting and drying cycles still resulted in water stable aggregation, but the effect was much smaller than when microbial activity was unrestricted.

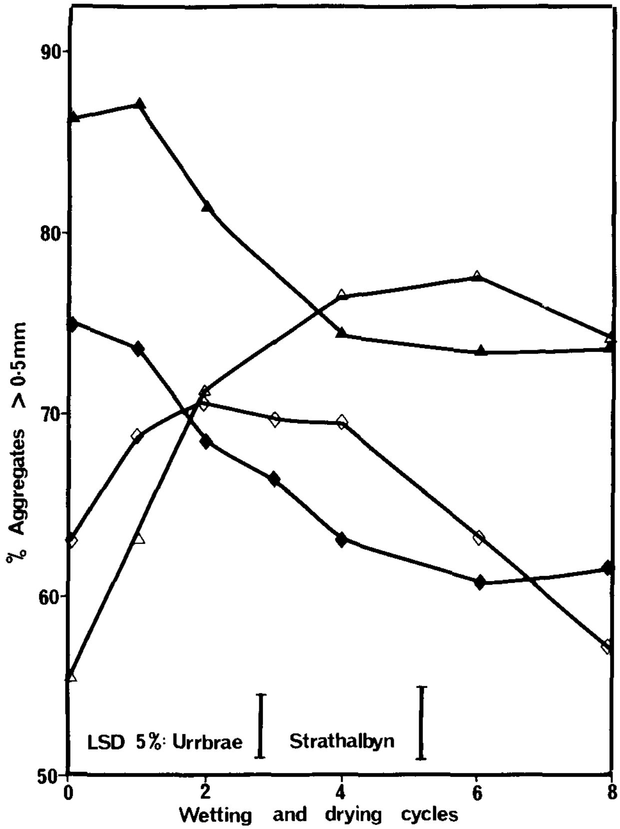

Fig. 3. Effect of wetting and drying cycles on the proportion of water stable aggregates. ◇, Urrbrae tilled; ♦, Urrbrae non-tilled; △, Strathalbyn tilled; ▲, Strathalbyn non-tilled.

Water stability of field aggregates

The proportion of water stable aggregates (which had not undergone wetting and drying cycles since tillage) in tilled soil was much smaller than that in non-tilled soil as shown in Fig. 3. This indicates that tillage destroys much of the previous bonding within soil aggregates. A decrease in aggregate water stability as a result of tillage was found by Rovira and Greacen (1957) in a simulated tillage experiment.

Fig. 3 also shows that the effect of artificial wetting and drying cycles on the proportion of water stable aggregates is different in tilled and non-tilled soil. For the aggregates collected from tilled soil, the water stability first increases with wetting and drying cycles up to four to six cycles, and then decreases with further cycles. The increase in water stability of aggregates disturbed by tillage in the first few cycles of wetting and drying is probably a manifestation of the reformation of the inter-particle bonds which have been destroyed by tillage. It has been suggested that soil disturbance by tillage makes available some of the organic matter previously unavailable for microbial activity (Rovira and Greacen, 1957). This can act as an energy source. It is suggested that soil microbial activity increases because of the newly available

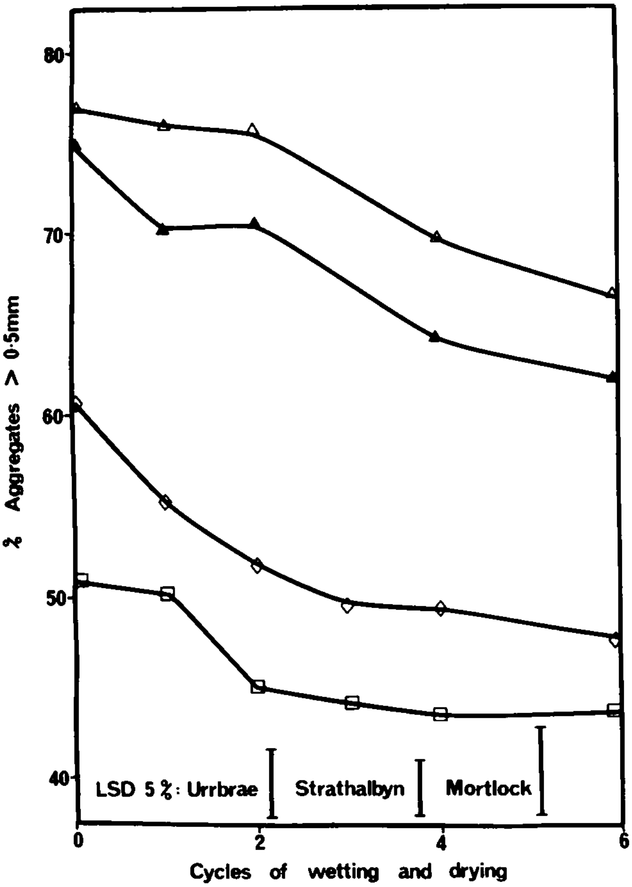

Fig. 4. Effect of wetting and drying cycles on the water stability of field aggregates as influenced by sterilization. ◇, Urrbrae tilled sterilized; □, Strathalbyn tilled sterilized; △, Mortlock non-tilled unsterilized; ▲, Mortlock non-tilled sterilized.

energy supply and that this results in the re-formation of organic bonds which have been destroyed by tillage. This bond re-formation might be speeded-up by the increased amplitude of soil wetting and drying which follows tillage. This increased activity is transient and has been observed through flushes of microbial respiration. The level of activity then returns to its original level or less. An increase in microbial activity with soil wetting and drying has been shown by several workers (e.g. Birch, 1958; Agarwal *et al.*, 1971).

An increase in the water stability of aggregates, which had been disturbed by tillage, after one cycle of wetting and drying was also found by Rovira and Greacen (1957). However, they did not extend their observations to further cycles. Tisdall *et al.* (1978), on the other hand, found that increasing numbers of wetting and drying cycles resulted in a steady reduction in the water stability of aggregates disturbed by 'tillage'. It seems likely that the 'tillage' treatment in their experiment, which consisted of passing the samples through a 4 mm sieve, did not provide sufficient

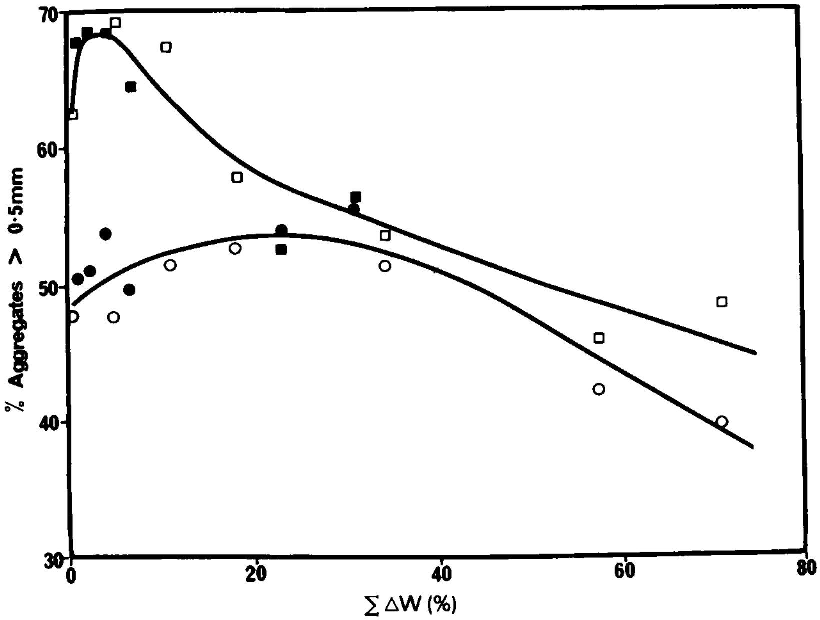

Fig. 5. Effect of natural wetting and drying, as shown by the cumulative amount of wetting and drying ($\sum \Delta w$) on the water stability of field aggregates of tilled Urrbrae soil. (a) Aggregates of 1.0–2.0 mm initial diameter from 0–5 cm (○) and 5–10 cm (●) layers; (b) aggregates of 2.0–4.0 mm initial diameter from 0–5 cm (□) and 5–10 cm (■) layers.

mechanical disturbance to make inaccessible organic matter available for microbial activity. Since there was no additional energy source, the micro-organisms were probably not able to replace the interparticle bonds which had been destroyed by wetting and drying. This suggestion is consistent with the result obtained here for the effect of wetting and drying cycles on the water stability of aggregates collected from non-tilled soil. These aggregates were collected by dry sieving the air dried soil and so little internal disturbance was caused to the aggregates. As shown in Fig. 3, after two to four cycles of wetting and drying, the water stability of these aggregates decreased significantly.

When wetting and drying cycles were applied to sterilized aggregates from the tilled soil, it was found that the proportion of water stable aggregates decreased steadily with increasing numbers of wetting and drying cycles as shown in Fig. 4. Again, this result supports the suggestion that the initial increase in the water stability of aggregates of tilled soil with wetting and drying is largely a consequence of microbial activity. A decrease in aggregate water stability of non-tilled soil both with and without sterilization was found also with Mortlock soil as shown in Fig. 4.

Changes following tillage

In the first few days after tillage, aggregate water stability increased with cumulative wetting and drying (Fig. 5) or with time after tillage (Fig. 6). After reaching a maximum value, water stability decreased with further wetting and drying or time after tillage. A crude comparison between results from the Urrbrae and Strathalbyn

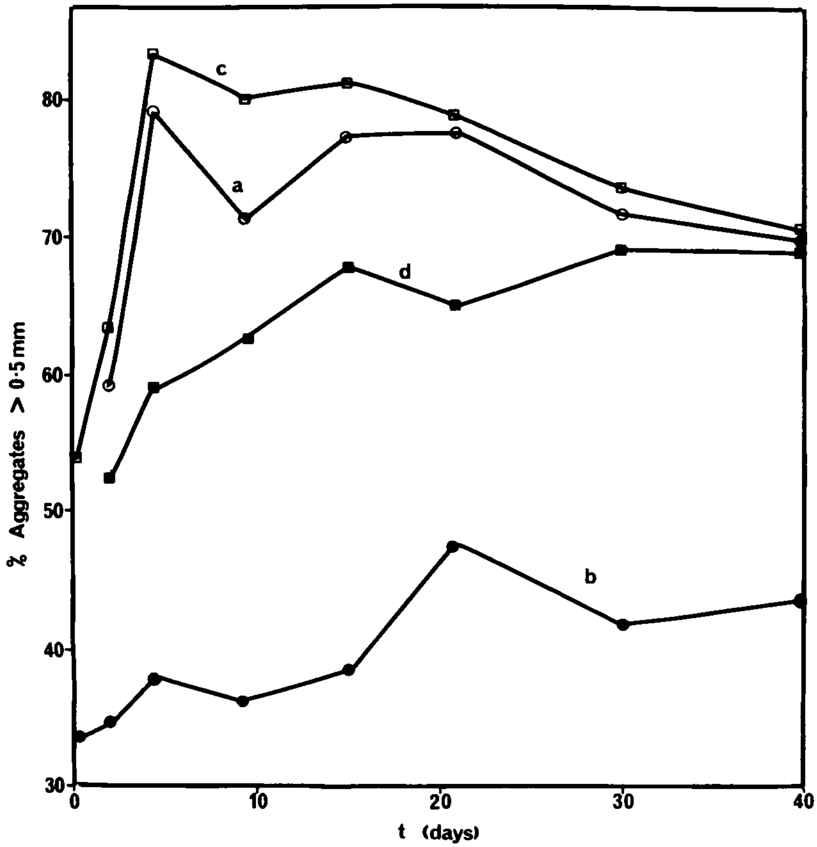

Fig. 6. Effect of natural wetting and drying, as shown by time (t) after tillage, on the water stability of field aggregates of tilled Strathalbyn soil: (a) aggregates of 1.0–2.0 mm initial diameter from 0–5 cm layer; (b) aggregates of 1.0–2.0 mm initial diameter from 5–10 cm layer; (c) aggregates of 2.0–4.0 mm initial diameter from 0–5 cm layer; (d) aggregates of 2.0–4.0 mm initial diameter from 5–10 cm layer.

sites can be made if it is assumed that the similar amounts of wetting and drying occurred in similar periods of time by using the approximate empirical relationships: $\sum\Delta w = 2.2t$ for the 0–50 mm layer, and $\sum\Delta w = 1.1t$ for the 50–100 mm layer, which were obtained for the tilled soil at the Urrbrae site and where t is the number of days since tillage. The similarities of the results of the two depths in Fig. 5 and the later peaks for the 50–100 mm depths in Fig. 6 support the use of $\sum\Delta w$ in the consideration of these effects.

The result of this field experiment is consistent with that found in the laboratory and illustrated in Fig. 3. As in the laboratory, the changes in aggregate water stability after tillage might have resulted from a combination of increased amplitude of wetting and drying and increased soil microbial activity. An approximate comparison between these results and those for artificially induced wetting and drying cycles in the laboratory reported above can be made with the $\sum\Delta w$ values in Table 3.

Table 3

Approximate cumulative amounts of wetting and drying $\sum \Delta w$, for samples in the experiments on the effects of sterilization on remoulded Mortlock and Urrbrae soils, and in the experiments on the water stability of field aggregates wetted and dried in the laboratory

	Approximate $\sum \Delta w$ (%)				
No. of wetting and drying cycles	*Remoulded*		*Field aggregates*		
	Urrbrae	*Mortlock*	*Urrbrae*	*Strathalbyn*	*Mortlock*
Control	6	1	0	0	0
1	27	14	21	26	13
2	48	27	42	52	26
3	69	40	63	78	39
4	90	53	84	104	52
6	132	79	126	156	78
8	–	–	168	208	104

Conclusions

The results of the experiments discussed above show that wetting and drying significantly influence water stable aggregation.

All the results obtained so far are consistent with the hypothesis that, in non-aggregated soil, wetting and drying creates planes of weakness which provide the initial faces of aggregates. The existence of these planes of weakness allows the soil to break-up into smaller aggregates when mechanical stress is applied by the wetting-up and agitation of the wet sieving procedure. It is therefore suggested that, a few days before tillage of a non-aggregated soil, it might be worthwhile to increase the amplitude of soil wetting and drying. This can be achieved by, for example, stubble clearing. This will, for some soils at least, cause the formation of planes of weakness. On tillage, such soils would then also crumble more readily into a seed bed through this 'tilth mellowing effect' (Utomo and Dexter, 1981*a*).

The effect of wetting and drying cycles on the water stability of aggregated soil is influenced by the recent history of the aggregates. It has been shown, both in the laboratory and the field, that wetting and drying first increases the water stability of aggregates disturbed by tillage to a maximum value: after this maximum, further wetting and drying decreases the water stability. For undisturbed aggregates, an increased amplitude of wetting and drying decreases the aggregate water stability.

It may seem paradoxical that wetting and drying can both cause water stable aggregation and can reduce the water stability of aggregates within the same soil type. This problem can be resolved by the introduction of the concept of equilibrium states of soil. We introduce the hypothesis that for any given soil composition and physical environment history, there is an equilibrium proportion or range of proportions of water stable aggregates. Soil which has less than the appropriate equilibrium value will increase its proportion, and soil which has more than the appropriate value will decrease its proportion. A change in soil surface management by, for example, tillage, cropping, or stubble burning, will change the value of the equilibrium proportion. The proportion of water stable aggregates does not change instantaneously, but approaches a new equilibrium value in a complex way depending on soil type, thixotropic effects, wetting and drying cycles, and microbial activity.

The findings reported in this paper may be capable of explaining many of the apparent inconsistencies in earlier work. Most of these apparent inconsistencies may have arisen from differences in experimental conditions and from the failure to distinguish between physical and micro-biological factors.

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