AERATION, TILLAGE EFFECTS ON

D.J. Horne
Massey University, Palmerston North, New Zealand

R.E. Sojka
Soil Scientist, Kimberly, Idaho, U.S.A.

INTRODUCTION

Few land management practices have the potential to impact upon soil aeration as directly or rapidly as tillage. Indeed, often, the reason for performing tillage is to modify or improve soil physical properties including aeration. The problems associated with inadequate aeration have been comprehensively reviewed elsewhere (1, 2). Important effects of limited soil aeration in crop production are: altered nutrient dynamics, a shift from oxidative to reductive chemical/biological reactions, impaired plant growth, and changes in gas equilibria affecting both soil and ambient atmospheres. For example, consider the soil nitrogen cycle which aeration effects via its influence on denitrification and gaseous nitrogen losses, decreased nitrogen mineralization rate and a reduction in nodulation and symbiotic fixation by leguminous plants (3). If the oxygen supply is sufficiently limited, and anerobosis sets in, then the products of reduction reactions may accumulate to toxic levels. In addition, a depleted oxygen supply may constrain root form and function, such as water and nutrient uptake, and therefore plant shoot performance even when many other soil physical factors are favorable (4). Unfortunately, relatively short periods of oxygen shortage can seriously compromise crop performance if they coincide with critical stages of crop growth (1). Finally, there are the effects of gas sources and sinks in the soil and transformations of soil gaseous components, and the exchange between soil and above ground air, on the atmosphere, e.g., diminished soil aeration may enhance the emission of greenhouse gases (5).

While the tillage-related literature is voluminous, little of it directly addresses soil aeration. Of necessity, this short article critiques only research which has measured aeration status directly—particularly indices of concentration and rate—and will make little or no attempt to draw inferences about the effect of tillage on soil aeration from studies reporting other related soil characteristics. Although bulk density, moisture content, and pore size distribution are related to soil aeration, and so may be indicative of aeration status, their direct relevance to a nuanced understanding of soil aeration is problematical. For instance, measurements of pore space convey little about pore continuity, tortuosity, or stability (6), whereas these effects are largely integrated de facto in measurements of oxygen diffusion rate (ODR).

EFFECTS OF SURFACE TILLAGE

Conventional tillage of virgin soil or soils growing permanent or long-term pasture for livestock grazing often improves soil aeration (7). In this situation, it is relatively straightforward to prepare a seedbed of good tilth and alleviate any compaction associated with animal or vehicular traffic. However, the timing of such plowing is important, as cultivation of wet soil leads to a dramatic reduction in soil aeration (8). If conventional tillage is poorly managed or executed in difficult circumstances (e.g., fine textured soils in humid climates) then relative to the permanent pasture datum, soil aeration may decline within a 3- or 4-year period (9). In the world's major cropping areas, tillage of pastureland is an infrequent occurrence; so a more interesting, if difficult, question is: what are the comparative effects of different tillage practices on soil aeration?

Accurately quantifying the effects of surface tillage on aeration has usually proved difficult. There are issues of both methodology and interpretation to contend with. For example, it has been argued that values for oxygen concentration in the seedbed say little about the quality of the soil air, or its rate of renewal where the roots or organisms are located, and that these factors are likely to be of greater importance than the average level for the whole soil (10). Also, some plants can compensate for low soil aeration by the supply of oxygen from one part of the root systems to another via internal diffusion. Another example relates to scale; what effect does a tillage practice have on intraaggregateo aeration in contrast to changes in aeration in the pore space between structural units where roots easily penetrate?

Interestingly, use of the ODR meter, arguably the best technique for field measurement of aeration status, is often unable to routinely and consistently discriminate between tillage treatments. This measure seems better able to reflect wet soil conditions associated with high rainfall and impeded drainage (11, 12). Yet a significant relationship between ODR and soybean yield has been observed, suggesting that it is only through critical stages of growth that low ODR will negatively impact on crop yield (12). Perhaps there are some implications here for the in-situ monitoring of the effects of tillage on aeration.

The difficulties mentioned above, and the sometimes conflicting research results that have been reported, mean that caution is required when attempting to draw broad conclusions about the effect of surface tillage on soil aeration. The impacts vary dramatically depending on: spatial heterogeneity, the depth in the soil profile under consideration (i.e., above or beneath the depth corresponding to plowing), soil type, the type or configuration of implements, climate, the cropping history of the field, the crop, the crop rotation, and the competency of the operator, especially regarding the timeliness of field work. The quantity and quality of crop residue may influence soil aeration; this aspect has received relatively little attention to date. Furthermore, interactions between aeration and other soil and crop properties make predictions about the exact effect of tillage on aeration risky. For example, aeration status may interact with earthworm populations and residue levels to effect seedling emergence (13).

The above discussion notwithstanding, most published literature has shown that surface soil is better aerated under conventional than other forms of tillage or that plowing enhances surface soil aeration to a greater extent than no tillage (14–16). The soil disturbance or loosening associated with tillage implements that invert or mix soil increases air movement in surface soil. In structurally degraded and/or fine textured soil, this increase in aeration may be confined to the inter-aggregate pore space. In an Indian study, tillage gave greater ODR than untilled (control) areas, and the greatest ODR was under moldboard plow and it was lowest with zero tillage (7). Likewise, in a compacted soil in New Zealand, rotary tillage of the soil surface improved ODR rates at 5-, 10-, and 15-cm depths compared with no-tillage (11). Enhanced rates of soil carbon oxidation are further evidence of improved aeration under cultivation.

The advantage that conventional tillage affords surface soil aeration may be somewhat transitory in nature both within seasons and across years. Enhanced soil aeration in a conventionally tilled seedbed may be short-lived as a result of soil reconsolidation (7), and may disappear by the time the crop becomes well established. The advantage of conventional tillage is likely to be more prominent early in the cropping cycle of a field: after many years of continuous cropping, no-tillage may be more beneficial to aeration status (17).

Although conventional tillage may generate more short-term macropores in the surface soil than no-tillage, they may not be as continuous down the profile and may be more tortuous (18–20). Therefore, no-tillage may improve aeration more uniformly throughout the soil profile particularly in the horizon just below the depth that corresponds to "plow level." Where sufficiently detailed measurements have been made, it would appear that not only may air permeability be more continuous or uniform down the profile under no-till, but it may also be more constant across "in rows" and between row positions (19).

Implement type will also have an important influence on the effect of tillage on soil aeration. In a summary of a number of New Zealand studies, the effects of some different drill openers on soil aeration are discussed (13). They demonstrate the benefits of some drill configurations (e.g., inverted T) relative to others (e.g., triple disk), and illustrate the importance of soil aeration to seedling establishment. In part, differences in tillage equipment, particularly direct-drilling machinery, may account for much of the disparity in the literature on the effects of tillage on aeration. For example, permeability measurements made under no-till treatments established using a triple disc are nearly always markedly inferior to those made under plowing (21).

EFFECTS OF SUBSURFACE TILLAGE

Subsurface tillage is practiced to improve aeration deeper in the profile where soils are naturally compact and/or have poor internal drainage. Where deep tillage is employed to improve drainage, it is important that there is an outlet for excess water or deep tillage may exacerbate aeration problems. In a study comparing deep tillage implements, the paraplow (angled shanks operating at 0.5 m depth) achieved more consistent improvement in air permeability at sowing, particularly in the important depth of 15–25 cm, than did subsoilers with straight shanks tilling at either shallow (0.25 m) or deeper (0.5 m) (11). In addition, all subsurface tillage treatments increased ODR values to a depth of 40 cm compared with the control. Due to reconsolidation in this humid climate, these advantages had disappeared by harvest.

The hypothesis that, as an alternative to conventional tillage, subsoiling in combination with no-tillage seeding would improve soil aeration, other physical properties, and crop yield in a soil that has become severely compacted following many years of cultivation has been tested (11). Some aspects of this study and a subsequent investigation (22) suggest that, for these New Zealand soils and conditions, despite the significant loosening achieved at depth by subsoiling implements, it was direct seeding that was the important component in the proposed system, and subsoiling contributed or added relatively little to the enhancement of crop yield. In part, this is due to the short-lived nature of the structural improvements generated by subsoiling (23).

TILLAGE, AERATION, AND GREENHOUSE GASES

In recent soil aeration research, there has been a shift in focus away from the study of the movement and use of oxygen and its effects on crop nutrition and growth to the role of soil aeration in environmental protection, e.g., greenhouse gas production and the susceptibility of nutrients to leaching. Indeed, concern about, and investigations of, the relationships between tillage and fluxes, composition and transformations of air into and out of soil is prominent on the environmental agenda. Of particular interest here is the effect of tillage practices on the release of the major greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) (5, 24). In addition, there is the suggestion that conservation tillage practices may enhance carbon sequestration (25).

Relative to no-tillage, conventional cultivation may result in greater CO_2 fluxes from the soil (26). No-tillage may increase the frequency of N_2O emissions and the net fixation of carbon by decreasing CO_2 emissions (5, 27). Periods of low or zero CO_2 fluxes and very high N_2O fluxes under no-tillage may be associated with periodic reduced gas diffusivity and air-filled porosity, both of which are often caused by heavy rainfall. In general, peak N_2O emissions are mainly associated with heavy rainfall following fertilization particularly with no-tilled soils (5). Plowing may decrease the oxidation rate of atmospheric CH_4 in aerobic soils but this is unlikely to be sufficient to offset the lower N_2O emissions from the soil (5).

SUMMARY

Adequate soil aeration is important to crop production and environmental protection. Tillage may profoundly influence soil aeration. Although the effect of tillage on soil aeration is dependent on a range of factors and is, therefore, hard to predict, often surface soil aeration is more favorable under well-managed conventional cultivation than no-tillage. Often, these improvements are confined to shallow soil depths and relatively short time intervals. Where appropriate no-till equipment is used, direct-drilling may have greater potential to improve soil aeration, both in terms of uniformity throughout the soil profile and permanence in time. Tillage practices that result in anaerobic soil conditions are likely to promote N_2O production, while those that disturb larger volumes of soil and promote aeration may result in greater emissions of CO_2.

REFERENCES

1. Glinski, J.; Stepniewski, W. *Soil Aeration and Its Role for Plants*; CRC Press Inc.: Boca Raton, FL, 1985; 229.
2. Scott, H.D. *Soil Physics: Agricultural and Environmental Applications*; Iowa Sate Press: Ames, IA, 2000; 421.
3. Lipiec, J.; Stepniewski, W. Effects of Soil Compaction and Tillage Systems on Uptake and Losses of Nutrients. Soil Till. Res. **1995**, *35*, 37–52.
4. Letey, J.; Stolzy, L.H.; Valoras, N.; Szuszkiewicz, T.E. Influence of Soil Oxygen on Growth and Mineral Concentration of Barley. Agron. J. **1962**, *54*, 538–540.
5. Ball, B.C.; Scott, A.; Parker, J.P. Field N_2O, CO_2 and CH_4 Fluxes in Relation to Tillage, Compaction and Soil Quality in Scotland. Soil Till. Res. **1999**, *53*, 29–39.
6. Francis, G.S.; Cameron, K.C.; Kemp, R.A. A Comparison of Soil Porosity and Solute Leaching After Six Years of Direct Drilling or Conventional Cultivation. Aust. J. Soil Res. **1988**, *26*, 637–649.
7. Khan, A.R. Influence of Tillage on Soil Aeration. J. Agron. Crop Sci. **1996**, *177* (4), 253–259.
8. Hodgson, A.S.; McLeod, D.A. Oxygen Flux, Air-Filled Porosity and Bulk Density as Indices of Vertisol Structure. Soil Sci. Soc. Am. J. **1989**, *53*, 540–543.
9. Shepherd, T.G.; Dando, J.L. Physical Indicators of Soil Quality for Environmental Monitoring. In *Proceedings of Soil and Land Indicators*; Hawkes Bay Regional Council New Zealand Technical report EMT 96/3 pp 33–42.
10. Dexter, A.R. Physical Properties of Tilled Soils. Soil Till. Res. **1997**, *43*, 41–63.
11. Sojka, R.E.; Horne, D.J.; Ross, C.W.; Baker, C.J. Subsoiling and Surface Tillage Effects on Soil Physical Properties and Forage Oat Stand and Yield. Soil Till. Res. **1997**, *40*, 125–144.
12. Flowers, M.D.; Lal, R. Axle Load and Tillage Effects on Soil Physical Properties and Soybean Grain Yield on a Mollic Ochraqualf in Northwest Ohio. Soil Till. Res. **1998**, *48* (1–2), 21–35.
13. Baker, C.J.; Chaudhary, A.D.; Springett, J.A. Barley Seedling Establishment and Infiltration from Direct Drilling in a Wet Soil. Proceedings of Agronomy Society of New Zealand, **1987**, *17*, 59–66.

14. Ball, B.C.; O'Sullivan, M.F.; Hunter, R. Gas Diffusion, Fluid Flow and Derived Pore Continuity Indices in Relation to Vehicle Traffic and Tillage. J. Soil Sci. **1988**, *3*, 327–339.
15. Ball, B.C.; Campbell, D.J.; Douglas, J.T.; Henshall, J.K.; O'Sullivan, M.F. Soil Structural Quality, Compaction and Land Management. European J. Soil Sci. **1997**, *48*, 593–601.
16. Rasmussen, K.J. Impact of Ploughless Soil Tillage on Yield and Soil Quality: A Scandinavian Review. Soil Till. Res. **1999**, *53*, 3–14.
17. Voorhees, W.B.; Lindstrom, M.J. Long-Term Effects of Tillage Method on Soil Tilth Independent of Wheel Traffic Compaction. Soil Sci. Amer. J. **1984**, *48*, 152–156.
18. Boone, F.R.; Van der Werf, H.M.G.; Kroesbergen, B.; ten Hag, B.A.; Boers, A. The Effect of Compaction of the Arable Layer in Sandy Soils on the Growth of Maize for Silage I. Critical Matric Water Potential in Relation to Soil Aeration and Mechanical Impedance. Neth. J. Agric. Sci. **1986**, *34*, 155–171.
19. Herad, J.R.; Kladivko, E.J.; Mannering, J.V. Soil Macroporosity, Hydraulic Conductivity and Air Permeability of Silty Soils Under Long-Term Conservation Tillage in Indiana. Soil Till. Res. **1987**, *11*, 1–18.
20. Carter, M.R. Characterizing the Soil Physical Conditions in Reduced Tillage Systems for Winter Wheat on a Fine Sandy Loam Using Small Cores. Canadian J. Soil Sci. **1992**, *72*, 395–402.
21. Schjonning, P.; Rasmussen, K.J. Soil Strength and Soil Core Characteristics for Direct Drilled and Ploughed Soils. Soil Till. Res. **2000**, *57*, 69–82.
22. Hamilton-Manns, M. The Effects of No-Tillage and Subsoil Loosening on Soil Physical Properties and Crop Performance M.Sc. Thesis, **1998**, Massey University, New Zealand.
23. Busscher, W.J.; Sojka, R.E. Enhancement of Subsoiling Effect on Soil Strength by Conservation Tillage. Trans. ASAE **1987**, *30* (4), 888–892.
24. Soane, B.D.; van Ouwerkerk, C. Implications of Soil Compaction in Crop Production for the Quality of the Environment. Soil Till. Res. **1995**, *35*, 5–22.
25. Lal, R. Residue Management, Conservation Tillage and Soil Restoration for Mitigating Greenhouse Effect by CO_2 Enrichment. Soil Till. Res. **1997**, *43*, 81–107.
26. Reicosky, D.C.; Reeves, D.W.; Prior, S.A.; Runion, G.B.; Rogers, H.H.; Raper, R.L. Effects of Residue Management and Controlled Traffic on Carbon Dioxide and Water Loss. Soil Till. Res. **1999**, *52* (3–4), 153–165.
27. Aulakh, M.S.; Rennie, D.A.; Paul, E.A. Gaseous Nitrogen Losses from Soils Under Zero-Till as Compared to Conventional-Till Management Systems. J Environ. Qual. **1984**, *13* (1), 130–136.