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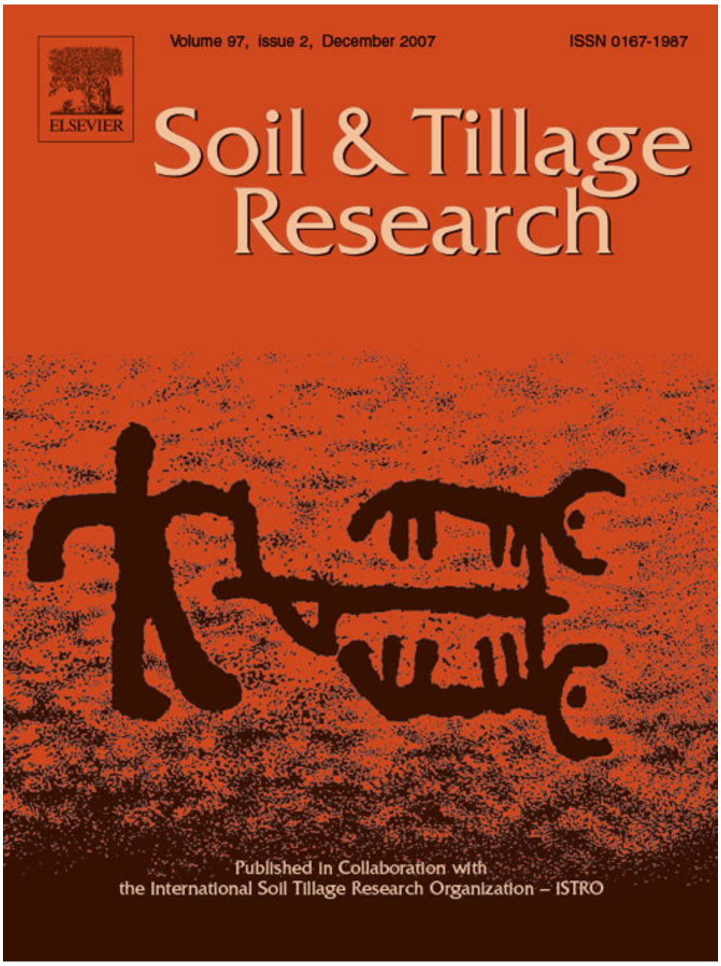

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Tillage and the environment in sub-tropical Australia—Tradeoffs and challenges

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Abstract

Tillage is defined here in a broad sense, including disturbance of the soil and crop residues, wheel traffic and sowing opportunities. In sub-tropical, semi-arid cropping areas in Australia, tillage systems have evolved from intensively tilled bare fallow systems, with high soil losses, to reduced and no tillage systems. In recent years, the use of controlled traffic has also increased. These conservation tillage systems are successful in reducing water erosion of soil and sediment-bound chemicals. Control of runoff of dissolved nutrients and weakly sorbed chemicals is less certain. Adoption of new practices appears to have been related to practical and economic considerations, and proved to be more profitable after a considerable period of research and development. However there are still challenges. One challenge is to ensure that systems that reduce soil erosion, which may involve greater use of chemicals, do not degrade water quality in streams. Another challenge is to ensure that systems that improve water entry do not increase drainage below the crop root zone, which would increase the risk of salinity. Better understanding of how tillage practices influence soil hydrology, runoff and erosion processes should lead to better tillage systems and enable better management of risks to water quality and soil health. Finally, the need to determine the effectiveness of in-field management practices in achieving stream water quality targets in large, multi-land use catchments will challenge our current knowledge base and the tools available.
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Keywords: Runoff; Erosion; Water quality; Pesticides; Deep drainage; Salinity

1. Introduction

In this paper we explore the relationships between tillage, the soil properties and crop residues that tillage affects, and off-site impacts on landscape hydrology and water quality. Tillage is considered in a broad sense, including disturbance of soil and crop residues, wheel traffic and sowing opportunities. These relationships are illustrated using example studies from sub-tropical, semi-arid cropping systems in eastern Australia. Important features of cropping in this region include the ability to grow summer and winter crops. Rainfall is summer dominant, but highly variable, of high intensity and erosivity. Evaporation exceeds rainfall, on average, in all months but cumulative rainfall can exceed cumulative evaporation for short periods (i.e. days to months) (Yee Yet and Silburn, 2003). Soils used for cropping are predominantly black, grey and brown Vertisols, with some important areas of Oxisols and Alfisols (Webb et al., 1997). A considerable proportion of soils have high erodibility (Freebairn et al., 1996), and saline or sodic subsoils (Shaw, 1997).

Natural resource management in the region in the past addressed the major issues of soil erosion (Freebairn et al., 1996) and decline in soil nutrients

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(Dalal and Probert, 1997) and structure (Connolly et al., 2001a), but is now increasingly concerned with dryland salinity (Shaw, 1997) and stream water quality (Rattray et al., 2002). Expectations of agriculture are changing, with the wider community now demanding more than just food as a product. Sustainable use of soils, high quality water and retention of biodiversity and habitat values are also expected outputs. In Australia, catchment management agencies are now expected to set land based and stream water quality targets, and to address these targets using management within the catchments. This requires a clear picture of the impacts of various tillage and cropping practices on hydrology and water quality at a variety of scales, which is a major challenge for research.

2. Evolution of tillage systems in sub-tropical Australia

Dryland grain and cotton cropping in the region traditionally involved growing annual summer or winter crops with periods of fallow to accumulate soil water to reduce the risk of crop failure. During the 1950s, it became clear that for cropping to be sustainable in this environment, control of soil erosion was essential. Contour bank (terraces) and grassed waterways (Titmarsh and Stone, 1997) were progressively implemented. However, bare fallowing was often practiced, with post-harvest stubble burnt or ploughed in, followed by frequent tillage to control weeds. Soil losses between contour banks were high, with rill erosion common, and occasionally banks were overtopped. For example, average annual soil losses of the order of 50 t/ha occurred on slopes of 4–7% (Freebairn and Wockner, 1986). Infrequent events with devastating soil losses of several hundred t/ha also occurred (Marshall et al., 1980). The seriousness of the erosion threat to sustainability is shown by simulation modelling indicating that on steep slopes (10%) and shallow soils (0.5 m) with bare fallowing, one half of the soil depth would erode in only 23 years (Loch and Silburn, 1997). In the early 1980s, a series of research studies were initiated on farms across Queensland and NSW. These compared the effects of various tillage systems on runoff and erosion, in small catchments (e.g. Freebairn and Wockner, 1986; Sallaway et al., 1990; Carroll et al., 1997) and with rainfall simulators (e.g. Loch and Donnollan, 1988), and on agronomy and fertility (e.g. Radford et al., 1992; Thomas et al., 1997). Modelling was used to integrate and extrapolate results in time and space (e.g. Littleboy et al., 1992; Freebairn et al., 1996). This research supported programs for development of reduced- and no-tillage farm machinery and improved herbicide application methods (Freebairn et al., 1993), and for extension involving farmers who, for a variety of reasons, were motivated to change practices.

Erosion control was found to be achievable using ‘conservation tillage’ within contour banks on steeper lands and within strip-cropping on flood plains (Freebairn and Wockner, 1986; Freebairn et al., 1996; Carroll et al., 1997). Use of land within a framework of land capability classification was also important, for instance, avoiding cropping on shallow soils or steep slopes (Stone and Titmarsh, 1997). Practical systems of farming evolved that included retention of crop residues on the soil surface through reduced tillage frequency and aggressiveness. Tillage and sowing equipment developed to allow cropping with stubble retained on the surface. Herbicides became more important for weed control, with improvements in application equipment and knowledge, the range and selectivity of products, and in some cases, lower costs relative to other farm inputs. While this was an important contribution to adoption of conservation tillage, it should be noted that herbicide use also increased in intensively tilled cropping systems, particularly for summer crops (Silburn et al., 2002).

Large reductions in soil erosion were obtained with tillage systems that retained greater cover (e.g. an order of magnitude, Freebairn and Wockner, 1986). Retaining cover also resulted in greater soil water storage, particularly in dryer seasons and with zero tillage, though experimental responses were variable and sometimes small (Radford et al., 1992; Freebairn et al., 1993; Thomas et al., 1997). Conversion of extra soil water to extra crop yield required optimal plant populations, control of plant diseases and reduction of nutrient limitations. Fixed fallow durations and annual crop rotations give limited opportunity to utilise the extra stored water. Continuing to fallow after filling about 80% of the soils available water capacity is highly inefficient, with losses to evaporation and runoff (Freebairn et al., 1996) and drainage below the root zone (McGarry et al., 2000; Tolmie et al., 2003a, b).

Conceptually, the extra soil water storage under reduced tillage and retained cover can be used productively, and water losses can be reduced, using ‘opportunity cropping’. This is a farming system where crops are sown when soil moisture is available rather than using a fixed rotation, resulting in more frequent but generally lower yielding crops (Freebairn et al., 1997). Freebairn et al. (1993, 1997) used water balance modelling to show that stubble retention reduced erosion but increased deep drainage relative to bare

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fallowing, for both continuous winter and summer cropping (1 crop/yr). However, deep drainage was reduced considerably using opportunity cropping to increase cropping frequency to 1.4 crops per year. Opportunity cropping gives a pattern of evapotranspiration, on average, that more closely matches the rainfall pattern than annual cropping (Freebairn et al., 1997). However, to realise there is an opportunity to sow a crop, farmers must know the soil water status in each field in near real time. Various tools have been developed to monitor soil water status in the field (including a simple steel 'push' rod) or calculate it from rainfall records (Freebairn et al., 1997; Dalgliesh and Foale, 1998). This approach to cropping seems well suited to the highly variable rainfall in semi-arid and sub-tropical environments.

The acid test of tillage systems is the level of adoption by farmers. Aspects of conservation tillage systems (reduced tillage, stubble retention, zero tillage and opportunity cropping) have been widely adopted in the region. Adoption appears to have been related to practical (i.e. improved planters and sprayers) and economic considerations, however the outcome is a win–win situation; conservation tillage systems eventually proved to be the most profitable systems. Well-designed farming systems (rather than any one practice) are more likely to be profitable and sustainable (Wylie, 1997). Drivers for change (for farmers) leading to adoption were equal or better profits, the ability to farm larger areas in less time with less capital tied up in machinery, and availability of new tillage and planting equipment and herbicide technology. Ultimately there are always some farmers who are continually looking for better ways to farm and they are generally ahead of the R&D at the practical level.

Another aspiration of reduced tillage systems is to prevent or reduce the decline in soil organic matter under cropping (Thomas et al., 1997). Soil carbon, nitrogen, phosphorous and other nutrients have declined with age of cropping in the region (Bridge and Bell, 1994; Dalal and Probert, 1997). The rate of organic carbon decline can be manipulated to some degree by tillage. For instance, the rate of decline will be slower with stubble retention (incorporated or on the surface) than where stubble is burnt. However, the overriding factor is the balance of inputs and removal.

More recently it has become apparent that the soil water storage response to retaining cover often has been limited because cropping land was generally subjected to random and frequent wheel traffic, resulting in compacted soil under the tilled layer (McGarry et al., 1999). Cover prevented surface sealing but infiltration was then limited by a compacted throttle layer at a shallow depth (5–15 cm) (Silburn and Connolly, 1995). During the 1990s, development and adoption of controlled traffic became widespread in broadacre farming (Li et al., 2001; Tullberg et al., 2001, 2003). Controlled traffic, zero till and opportunity cropping have many synergistic aspects. For example, retaining surface cover creates more opportunities for sowing by maintaining optimal moisture conditions in the surface soil. Controlled traffic improves the chance of taking up these opportunities by allowing machinery access over a wider window of soil conditions. Controlled traffic also allows more timely, accurate and effective spraying, making zero till easier to manage. Practical aspects of controlled traffic farming are discussed in Conservation Farmers (2003).

3. Soil hydrology and tillage effects

The hydrologic behaviour of soils is dependent on key soil layers that can act as restrictions to water entry (Silburn and Connolly, 1995; Connolly et al., 2001a) (Fig. 1). These soil layers may be inherent (e.g. horizons with fine texture, poor structure or sodicity) or induced by agricultural practices. Tillage can increase the prevalence of infiltration-limiting layers by exposing surface soil to raindrop impacts (causing surface sealing, Silburn and Foley, 1994) and contributing to structural degradation (causing seals to become more restrictive over time, Connolly et al., 2001a), and by creating smeared and compacted layers under the tilled layer (Silburn and Connolly, 1995; Silburn and Glanville, 2002) or on the surface (Li et al., 2001; Tullberg et al., 2001). Tullberg et al. (2003) present clear photographs of various types of compacted layers.

Infiltration restrictions on or near the soil surface are obviously more severe than deeper restrictions because rainfall is almost immediately lost to runoff. Connolly et al. (2001a) determined that surface sealing (crusting) was a large contributor to runoff from intensively tilled cropping on some soils, but deeper layers were more limiting on other soils less susceptible to sealing. Management practices generally only affect particular layers – retaining cover prevents surface sealing while controlled traffic aims to prevent compaction. The presence and response to management of various layers needs to be appreciated for successful design of improved management systems for different soils. Management of these soil layers also has implications for water quality and deep drainage, as discussed in later sections.

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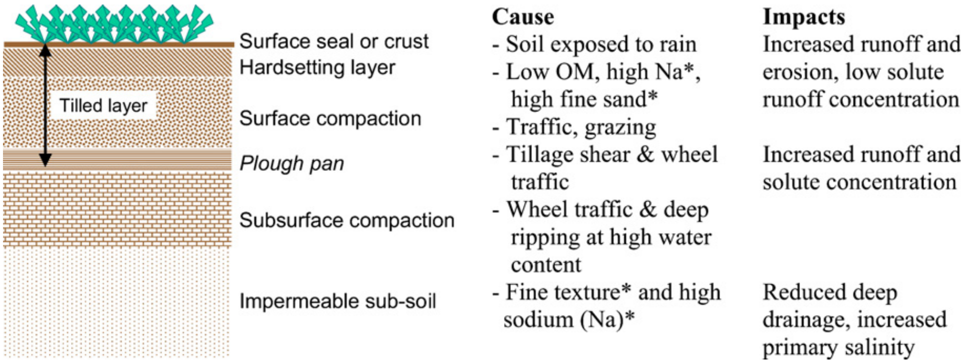

Fig. 1. Inherent (*) and induced soil layers that may restrict water entry (Source: Tolmie and Silburn, 2001).

4. Effects of tillage on water quality

Few catchment studies have been conducted to directly compare nutrient and pesticide runoff losses from different tillage systems in Australia, with no studies for dryland grain cropping. Thus we must base our interpretation and management advice on first principles and our basic understanding of hydrology and erosion processes, and on studies in irrigated cotton (e.g. Waters, 2001; Silburn et al., 2002) and from overseas, particularly the USA (Walter et al., 1979; Chichester and Richardson, 1992; Sharpley et al., 1991; Fawcett et al., 1994). Options for management of water quality include (i) controlling levels of pesticides and nutrients in the soil surface, through application rates, placement and timing, (ii) soil and water management within the field, which controls the transporting agents (water and sediment), and (iii) managing runoff after it leaves the field. Behaviour of sediments, nutrients and pesticides as they are transported (or lost) through farm waterways and stream networks has large implications for loads and concentrations in downstream receiving waters (Willis et al., 1987; Finlayson and Silburn, 1996). Pollutants are variously subjected to deposition, degradation, dilution, adsorption–desorption and volatilisation in transit. These processes are understood in principle but are difficult to specify in any particular catchment. Thus there is a considerable challenge for catchment management authorities in setting achievable streams water quality targets and deciding where within the catchment to invest in management practices to achieve them.

Soil and water management within the field is closely related to tillage practices, particularly their effects on crop residues and surface cover. In northern Australia, retaining cover on the soil surface by limiting tillage greatly reduces soil loss for various farming systems (e.g. Freebairn et al., 1996; Silburn and Glanville, 2002; Waters, 2001) and therefore will be effective in managing runoff of chemicals sorbed to sediment. However, the response of fine suspended particles (which maybe enriched in organic matter and sorbed chemicals) and nutrients and pesticides in the solution phase (i.e. not sorbed to sediment) is less clear.

4.1. Pesticides

In a review of studies in the United States, Fawcett et al. (1994) found that conservation tillage, defined as retaining a minimum of 30% crop residue cover after sowing, usually reduced runoff losses of pesticides (mostly herbicides) from cropped lands compared with conventional (bare, tilled) but some data were conflicting. For herbicides, the average reductions across all natural rainfall studies were 70, 69 and 42% for no-till, chisel plow and ridge-till, respectively. This was in spite of the fact that many of the herbicides were carried off in the solution phase rather than by being adsorbed to entrained sediment. In this case, reductions in pesticide losses were associated with the degree to which the treatment reduced the amount of runoff. However, for individual studies, herbicide runoff from no-till varied from none to twice that from conventional. These studies all had equal application rates on the tillage treatments.

Pesticide runoff potential is related to the amount of chemical used, or more directly, the concentration of chemical in the soil surface at the time of runoff. Reduced tillage, and especially no tillage, generally relies on replacement of tillage with herbicides for weed control. However, use rates are not necessarily less with more intensively tilled systems. Residual herbicides are often applied at sowing irrespective of the fallow tillage system, particularly for summer crops. Insecticide use is largely independent of the tillage system. During fallows, tillage is often replaced by use of ‘knockdown’ herbicides that are generally of lower environmental risk (tightly sorbed, rapidly dissipated). If it is accepted

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that erosion control is essential in croplands and weed control is needed, then retaining surface cover and use of herbicides that are strongly sorbed to soil will be complementary. However, some residual herbicides (e.g. atrazine) still pose risks because they are intrinsically less strongly sorbed (so they can translocate into weeds) and are relatively more persistent in soils.

Assessing and managing pesticide in runoff is complicated because: (a) management depends on the pesticides sorption properties (which vary widely for different pesticides) that determine the proportion transported in solution or in sediment, and (b) concentrations in the soil decrease over time after application (e.g. by five orders of magnitude) but the rate of dissipation varies widely for different pesticides (Hornsby et al., 1996). Dissipation refers to the reduction in pesticide concentrations in soil over time, by any mechanism e.g. degradation, volatilisation. Knowledge of pesticide behaviour for local climatic and soil conditions enables a more reliable assessment of risk. Studies in inland Queensland (Rattray et al., 2002; Silburn, 2003) and in coastal Queensland (Simpson et al., 2001) indicate more rapid dissipation of many pesticides in soil than reported elsewhere (Hornsby et al., 1996), particularly in the surface soil layer contributing to runoff. This layer is exposed to greater climatic extremes and volatilisation losses than deeper soil layers. Thus runoff risk may be lower than determined from published chemical persistence data. Even so, the most widely used residual herbicide in the northern grain areas, atrazine, is continuously detected at low levels in nearby rivers (CBWC, 1999).

It is now clear that two-phase sorption or mobile-immobile processes affect pesticide behaviour in field soils (Brusseau and Rao, 1989; Silburn, 2003; Wauchope et al., 2002). This has several consequences. One is that soil sorption coefficients increase with time after application (Simpson et al., 2001; Silburn, 2003). Thus pesticides that are considered poorly sorbed, based on short-term laboratory studies, exhibit greater partitioning into soil solids and in the sediment phase in runoff with greater time of contact with soil. Such pesticides are somewhat more amenable to management by erosion control practices a few days or weeks after spraying than expected from short-term studies. Conversely, sorption of otherwise tightly sorbed pesticides can be poor in the first few hours after spraying and there is an increased risk of runoff in the solution phase; as there has been little time for dissipation and movement into the soil, extreme concentrations in runoff can occur if a storm occurs at this time. At short times after spraying, the pesticides have not yet diffused into the interior of soil aggregates or deeper into the soil. These processes also have consequences for conducting and interpreting pesticide runoff studies. For instance, high concentrations of pesticides measured in runoff from rainfall simulator plots run soon after spraying (Wauchope, 1978; Leonard, 1990) are 'real' but only represent this particular time after spraying. Also, models that include two-phase sorption give improved predictions of pesticide behaviour in soil and runoff (Truman et al., 1998). A further outcome of two-phase (or multi phase) behaviour is that pesticide dissipation in soil often does not exactly follow first-order (exponential) decay, rather half-lives increase with time of contact, in part because the more sorbed (immobile) phase is subjected to less (or no) dissipation. The model of Truman et al. (1998) correctly predicted such behaviour.

In a case study in irrigated cotton in Australia, management practices for reducing runoff of pesticides were tested using rainfall simulator studies, modelling and on-farm catchment studies. Rainfall simulator studies were used to 'screen' various management practices. Retaining crop residues on the soil surface under cotton was found to be effective (Silburn and Glanville, 2002; Silburn et al., 2002). Simulation modelling extended these results over a longer series of climate and patterns of spraying and dissipation (Connolly et al., 1999, 2001b). When management practices were trialled on commercial cotton fields over several years, cotton grown in wheat stubble gave considerable lower sediment, nutrient and pesticide runoff losses than the traditional practices of cotton planting into bare soil (Waters et al., 1999; Waters, 2001). Retaining cover under cotton created difficulties in establishing the cotton e.g. maintaining raised beds, applying fertiliser and soil-residual herbicides, and irrigation scheduling and furrow irrigation tactics needed to be redefined. Many of these challenges were overcome in practice. The wheat–cotton rotation also had unanticipated benefits. Firstly, there was a reduction in the pest insect pressure and fewer applications of insecticides were needed. Secondly, rapid dissipation of endosulfan (an insecticide of concern as an aquatic pollutant) occurred on crop residues, thereby reducing pesticide runoff more than expected from simply reducing sediment and water losses (Silburn, 2003). Comparatively little is known about behaviour of pesticides on crop residues and the resulting effects on runoff losses and weed control efficacy.

In summary, there are considerable challenges in understanding the risks and managing runoff of the

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large number of pesticides (with diverse properties) in use, and in using (convenient) laboratory studies to determine likely behaviour in the field. Field studies of dissipation, partitioning and runoff losses under local conditions greatly reduce the uncertainties involved (e.g. Simpson et al., 2001; Silburn, 2003).

4.2. Nutrients – nitrogen (N) and phosphorus (P)

Conservation farming practices usually reduce both concentrations and total losses of sediment-associated chemicals, due to their effectiveness in controlling sediment movement. However, for nutrients transported in runoff in the dissolved phase (e.g. NO_3-N, NH_4-N and PO_4-P) a review of US studies by Baker and Laflen (1983) indicates that many conservation tillage systems gave significantly higher concentrations and losses than intensively tilled systems. Fertiliser placement is an important consideration and conservation tillage, particularly no-till, can have negative consequences for water quality if it involves surface (non-incorporated) fertiliser application. Many (but not all) studies where dissolved N and P in runoff increased with greater cover involved surface-applied fertiliser which was then incorporated, with less or no incorporation for higher cover systems. Where fertiliser was applied subsurface, concentrations of dissolved N and P in runoff were similar, or decreased, with greater cover (e.g. Chichester and Richardson, 1992). However, one study (McDowell and McGregor, 1984) found no-till had somewhat increased annual NO_3-N losses (probably due to higher soil N status) and dissolved P losses increased considerably (attributed to increased release of P from crop residues).

Losses of dissolved N and P in runoff are often a small proportion of total losses from erosive situations, being out-weighed by losses associated with sediment. Runoff losses of dissolved N are sometimes less than the input from rainfall. Runoff losses of dissolved nutrient forms are limited because, firstly, they are commonly a small proportion of the total N or P in the soil, and secondly, because of leaching of dissolved chemicals out of the soil surface before runoff begins. Even so, dissolved N and P may be of concern, as they are more readily available forms of nutrients in aquatic systems and do not settle-out as occurs with sediment-bound nutrients. In contrast, losses of dissolved N and P contribute a larger proportion of total losses where runoff volumes are high or where sediment loads are reduced due to low slope or high cover. Chichester and Richardson (1992) report dissolved N and P losses from conventional till cropland equal to half the total losses, because annual runoff was reasonably high (130 mm/yr) and total sediment loss was reasonably low (1.6 t/ha), because of the low slope. For land uses that maintain high soil cover, such as well-managed pastures, dissolved losses can dominate, e.g. 70–90% of total P (Nash and Halliwell, 1999). Dissolved N and P is sourced from plants and plant residues as well as from soil, thus runoff of dissolved P may be greater from grasslands than from croplands (Sharpley et al., 1991). Dissolved concentrations and losses can be considerably greater where interflow or lateral subsurface flow contribute to runoff (Baker and Laflen, 1983; Cox and Pitman, 2001).

One study particularly relevant to eastern Australia is that of Chichester and Richardson (1992) in Texas, USA. Conditions were reasonably similar to broad-acre cropping in northern NSW and Queensland; black cracking clay (1.6% organic carbon), low to moderate N and P status, slopes of 1–3%, wheat, sorghum and maize grown in rotation, though annual rainfall (867 mm) is higher and seasonal distribution more uniform in Texas. They found no-till (with controlled traffic) gave runoff similar to conventional tillage (5–6 cultivations per fallow), reduced losses of sediment by an order of magnitude and halved total N and total P losses. Losses of sediment sorbed N and P were reduced 7–80-fold, consistent with the reduction in sediment losses. Losses of dissolved N (the major N loss) were reduced by about half. Losses of dissolved P (half the total P lost) were not affected by tillage practice. Runoff losses from conventional tillage represented 6% and 12% of N and P fertiliser applied, respectively.

In northern Australia, retaining cover on the soil surface by limiting tillage has been found to reduce soil loss for various farming systems (e.g. Freebairn et al., 1996; Silburn and Glanville, 2002). Consequently, runoff losses of sediment-sorbed chemicals would be expected to be lower. This is illustrated by data from cotton furrows using a rainfall simulator (Fig. 2a) – concentrations of sediment-bound N in runoff decreased with increasing cover because sediment concentrations in runoff decreased with cover (Silburn and Glanville, 2002). Prior wheel traffic had little effect on concentrations of sediment and sorbed nutrients, but did influence the total losses because runoff was greater from wheel tracks. Similar results were found for sediment transported P in runoff and for total P in runoff (data not shown), as most P was sediment bound with little in dissolved forms.

In contrast, total dissolved nutrient concentrations in runoff (dominantly NO_3-N, with some NH_4-N and organic N) increased with cover, particularly for wheel

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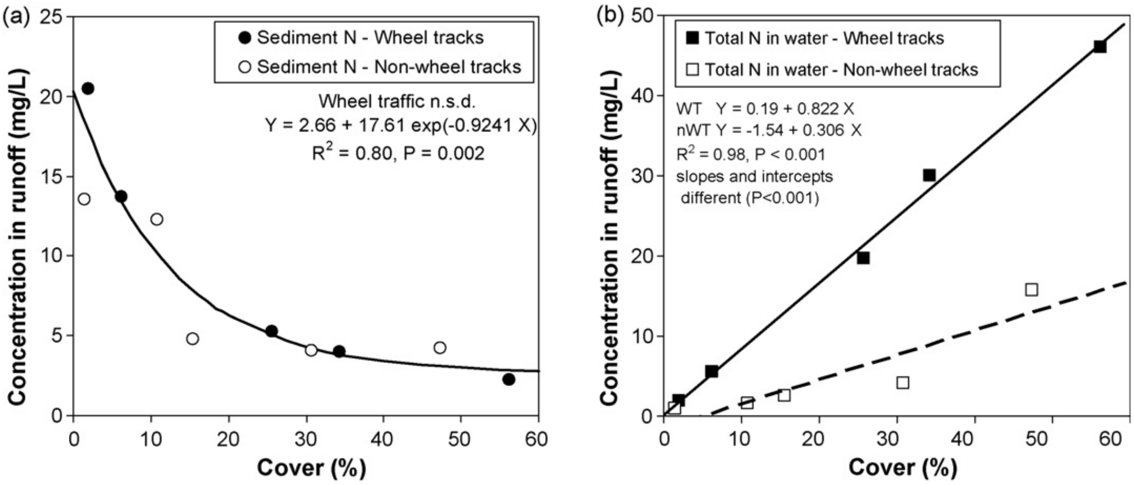

Fig. 2. Concentrations in runoff, from cotton furrows with and without wheel traffic for a range of cover, of (a) N in sediment and (b) total N dissolved in water. (Silburn and Hunter, unpublished data).

tracks (Fig. 2b). Concentrations of NO_3-N in runoff were relatively high because of high input of nitrogen fertiliser and resulting high soil NO_3-N levels. Total losses of N and P in runoff decreased with greater cover because runoff amount decreased with cover. However, losses of dissolved chemicals increased with cover on wheel tracks and decreased on non-wheel tracks.

In this rainfall simulator study, runoff of dissolved chemicals was influenced by interactions of cover and wheel traffic, which affect processes of infiltration and runoff generation as discussed above (Section 3, Fig. 1). Concentrations of dissolved N in runoff from soil with low levels of cover (wheeled and non-wheeled) were low because infiltration before runoff began leached soluble N from the soil surface and it was not available to be entrained after runoff began. The infiltrated water and dissolved N never reappeared in runoff. On covered plots, runoff occurred due to restriction of infiltration into the compacted subsoil, rather than by surface sealing. A saturated layer of surface soil was created with high concentrations of dissolved N, particularly on wheel track plots, where movement of water and dissolved N into the compacted subsoil was most restricted. The dissolved N leached from the surface early in the event thus returned in runoff later in the event. This led to relatively high concentrations of dissolved N in runoff from soil with high levels of cover, particularly on wheel track plots. However, runoff concentrations of chemicals with even a slight sorption to soil, such as dissolved P and the herbicide prometryn, were not as greatly increased (results not shown). Apparently these chemicals were partially 'filtered' (sorbed) in the soil during infiltration and later exfiltration of water.

This study illustrates that different infiltration and runoff generation processes can lead to different water quality responses to tillage and cover treatments. Suppression of downward leaching near the soil surface and shallow interflow on a throttle layer is a worst-case scenario for runoff transport of dissolved chemicals.

5. From field to stream

A challenge confronting catchment management authorities is to determine what land management practices, implemented at hillslope, paddock or field scales, will deliver water of a quality that meets targets in streams and rivers at some distance down the catchment. 'End-of-catchment' water quality is influenced by the mix of land uses in the catchment, their contributions of water and pollutant loads, their distribution relative to the stream network, and by in-stream processes. Cropping may occur in a small proportion of the catchment (e.g. $<5\%$ in the 87,300 km^2 Condamine-Balonne in Queensland) or a large proportion (e.g. $>50\%$ in the 566 km^2 Hodgson Creek, near Toowoomba). Cropped fields may be scattered throughout the catchment, some close to drainage lines, some at considerable distance. Concentrations of sediment, pesticides and nutrients are generally considerably greater at edge-of-field or hillslope scales than in streams and rivers (Leonard, 1990). As the distance from the source increases, concentrations are generally reduced by deposition of sediment, dilution (with 'cleaner' water), dissipation (chemical and biological degradation, volatilisation) and adsorption. Willis et al. (1987), for example, provide a classic case study for two pesticides.

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Sediment may also be sourced from gully erosion in drainage lines and stream bank erosion. However, relationships between water quality and catchment size are complex in catchments with mixed land uses, depending on the spatial distribution of land uses, the stream network and rainfall during individual events. Separating out the contribution of cropped areas and their management to the improvement in water quality is therefore complex.

In the Darling Downs region in Queensland, Rattray et al. (2002) studied the effects of scale on the runoff transport of sediment, total nitrogen (TN) and phosphorus (TP) in the Hodgson Creek catchment (Fig. 3). ANZECC (2000) 'trigger' values are exceeded all of the time. The smallest scale shown, 38 ha, is associated with 70% cropping and 30% grazing, and slopes of 2–15%, enhancing the production of sediment, TN and TP. The two larger scales each include about 50% cropping, 45% grazing and 5% other land uses. Cropping in the 38 ha catchment involved conventional tillage between contour banks while the larger catchments involved a range of tillage practices. The decrease in TN and TP concentrations with larger catchment size is probably associated with deposition of sediment in various locations, such as valley floors and the lower reaches of the channel system, which have lower slope and, in parts, are more vegetated. Through the various catchment scales, TP concentrations are highly correlated with sediment concentrations and TN concentrations are reasonably well correlated with sediment concentrations, because most N and P are in sorbed forms. Higher flows are associated with higher sediment, TN and TP concentrations, and contribute the greatest proportion of total loads. The streams are ephemeral and baseflow is estimated to be only 2.5% of flow (1987–2001).

This study showed that cropped land produces higher concentrations of sediment and nutrients (and higher runoff volumes) than the surrounding multi-land use catchments. Tillage practices for reducing these losses from cropped lands are discussed in previous sections. The questions remaining here are: what will be the impact of tillage practices at the larger catchment scales? Will they (alone) result in achieving the water quality targets? What level of adoption is required? Is adoption achievable and economic? The spatial distribution of adoption will also be important. Davie and Lant (1994) found that conservation activities near the stream network were much more influential on end-of-catchment sediment loads that those conducted further from the streams.

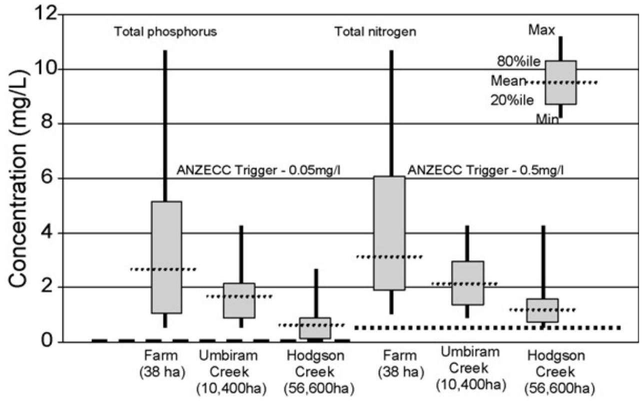

Fig. 3. Total nitrogen and phosphorus concentrations for three catchment scales (1999–2002), (Source: Rattray et al., 2002).

The Hodgson Creek case study also illustrates that natural processes can improve water quality through a catchment, in this case, mainly by sediment deposition. However, visual inspection of the catchment channel network indicates many reaches with an absence of vegetation and roughness that would enhance filtering, with grazing by cattle a common practice. Thus more could be done to enhance these processes while only impacting on land use in a small proportion of the catchment. Owens et al. (1996) document an example of this and show that sediment load was decreased by 40% as a result of the exclusion of stock from streams and riparian zones. While the major beneficial effect of this practice appeared to be the stabilisation of near-stream sediment sources, improvement in the filtration effect of riparian vegetation may also be important.

Even so, it is not a good idea to allow or encourage poor practices in-field, on the basis that it can be cleaned up off-site. One reason for this is that sediment deposited in the stream network is notorious for remobilising in later times (sometimes much later) (Finlayson and Silburn, 1996). Large sediment masses from poorly managed fields can also exceed the sediment storage capacity of near- and in-stream measures (Marshall et al., 1980). The near- and in-stream locations are themselves part of the environment where we are trying to protect water quality values and should not be seen as a good place to 'dispose of' sediment. However, the combination of best in-field practices and near- and in-stream practices is highly synergistic, maximising the natural processes that can assist in improving water quality.

Success in understanding the impacts of in-field management practices on catchment water quality in multi-land use catchments requires a combination of field studies on single-land use catchments (e.g. comparing tillage systems), nested catchment monitoring and models that can connect these scales, as illustrated by Rattray et al. (2002), Dougall et al. (2003)

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and Rohde et al. (2003). The 'Neighbourhood' catchment approach of Carroll et al. (2002) combines these approaches with involvement of the community, land owners and managers to achieve ownership and change in catchment and stream management.

6. Effects on deep drainage

In recent years there has been increased interest in drainage below the plant root zone in the northern Australian cropping zone, because of emerging concerns about dryland or secondary salinity. Recent studies in the Queensland Murray-Darling Basin investigated this issue using soil chloride mass balance (Tolmie et al., 2003a, b), lysimetry (Foley et al., 2003) and water balance modelling (Yee Yet and Silburn, 2003). These studies (mainly on Vertosols and Sodosols) indicate that (a) drainage was low under native vegetation and considerable salt was stored in soils across the region, (b) drainage is consistently higher under cropping than under native vegetation, and (c) considerable downward movement of chloride and other salts has occurred since clearing, e.g. 50% of the chloride was lost from the surface 0–1.5 m of soil in 20–50 years.

Tillage also affected deep drainage, although the response varies between sites. At a wetter eastern cropping site, more soil chloride moved downwards and drainage was greater under zero till than conventional tillage in 34 years of annual winter crops (Fig. 4a). McGarry et al. (2000) also observed greater loss of soil chloride under zero till than conventional tillage in central Queensland (665 mm/yr rainfall). In contrast, at a drier western site, chloride movement was similar for zero till and conventional tillage annual wheat crops (Fig. 4b) but was less for opportunity cropping where water use coincided more closely with the rainfall pattern.

Under the higher drainage rates with cropping, soil chloride and other solutes will decline over time to establish a new equilibrium. For example, transient chloride mass balance analysis on data from a grey Vertosol (Fig. 5) indicates some 50 years to approach, and over 200 years to reach, a new equilibrium with the higher drainage rate. This represents loss of some 15 t/ha of chloride from the surface 1.5 m of soil, and an unknown amount from the regolith, moving down into the regolith or laterally in the landscape. The consequences of this increased deep drainage and movement of salts for salinity, groundwater and stream water quality in the northern cropping regions are uncertain.

Improved water entry with stubble retention and controlled traffic can result in increased drainage below the crop root zone (Bell, 2001). This increases the risk of salinity and contamination of groundwater. The recent wide scale adoption of controlled traffic, and resulting improved subsoil structure, will presumably reinforce this effect. The challenge is to convert the extra stored soil water into crop transpiration rather than into deep drainage, by better matching the crop water use pattern with the rainfall pattern, for example, by increasing the number or duration of crops. This is illustrated by the case of farming on Red Ferrosols, described below.

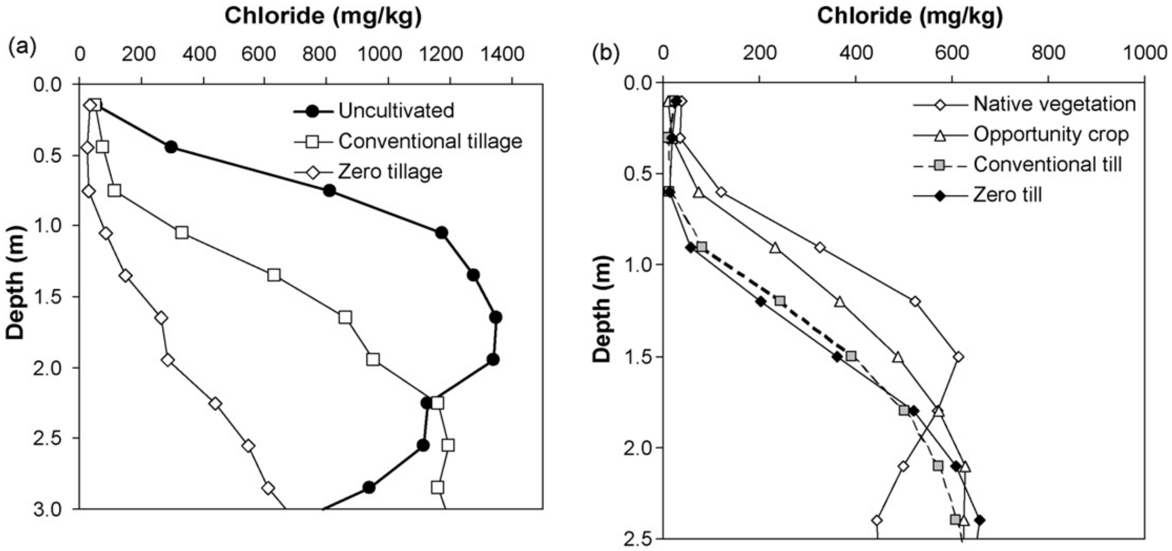

Fig. 4. Soil chloride for uncultivated and tilled treatments for (a) 34 years of annual winter cropping on a Black Vertosol, 'Hermitage' eastern Darling Downs, rainfall 670 mm/yr and (b) Grey Vertosol, 'Nindigully' western cropping, rainfall 500 mm/yr (Source: Tolmie et al., 2003b).

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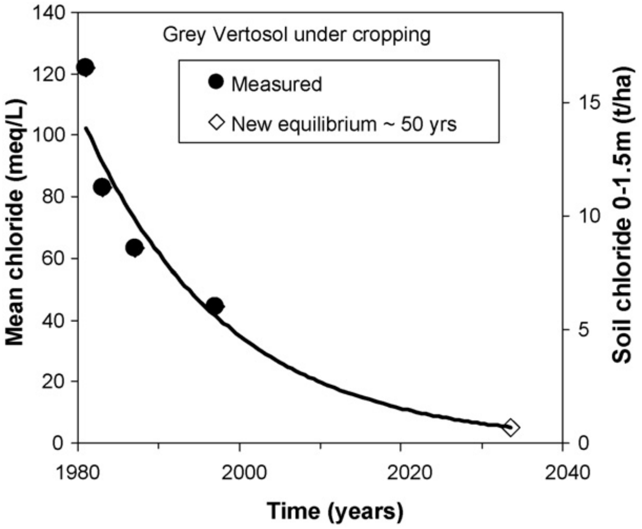

Fig. 5. Change in mean soil chloride in a 1.5 m deep soil profile after clearing of native vegetation and use for cropping. The new equilibrium is calculated for the increased drainage rate (Our interpretation of unpublished data from B. Cowie, personal communication).

6.1. Solving one problem, creating another and solving it

In studies on Red Ferrosols (Bell, 2001) (Krasnozem and Euchrozem soils formed on basalt), characterised by low water storage capacity (90–110 mm), infiltrations rates that were originally relatively high but declined after long term cropping due to surface crusting and soil compaction, leading to increased runoff and soil loss. This can be overcome by reversing the decline in soil organic matter, using various combinations of pasture leys, deep ripping and reduced or zero tillage (Bridge and Bell, 1994; Bell et al., 1997). Despite possible increased cropping opportunities associated with conservation tillage systems, increased rainfall infiltration did not necessarily result in improved crop yield. Rather, much of the enhanced infiltration became deep drainage. Bell (2001) considered this hard to avoid, because of the low water storage capacity of the soils and the distribution of rainfall (isolated, often multiple, events). Rising groundwater levels and salinity or water logging are now evident in mid and lower slope positions in these landscapes. An integrated approach to land management is now being adopted, reducing drainage as much as possible by increasing crop frequency on crop lands, use of shallow interception trenches (where water is not saline and can be recycled for irrigation) and planting deep-rooted trees at strategic positions. Fortunately, eucalypt-based farm forestry appears suited to and viable in the region.

7. Conclusions

In the sub-tropical semi-arid cropping areas of Australia, conservation tillage continues to be adopted and controlled traffic is becoming more widespread. Conservation tillage and controlled traffic can improve infiltration, and potentially increase soil water storage and crop production. However, careful management of soil water is required to convert this extra soil water into crop yield and to minimise drainage below the root zone. This requires flexible cropping systems (‘soil water – use it or lose it’) in the highly variable rainfall regime of the semi-arid tropics and sub-tropics. An understanding of soil hydrology, including water holding capacity and soil layers that restrict infiltration, assists in designing and managing such cropping systems. These tillage systems reduce the risk of soil erosion and runoff of sediment-bound nutrients and pesticides. However, it is less clear that runoff losses of dissolved chemicals are reduced. Few studies are available comparing water quality from the main cropping and tillage systems, which creates uncertainty in management of regional water quality targets. In-field and off-site management practices, which are synergistic, are both needed to achieve these targets. The need to determine the effectiveness of in-field management practices in achieving stream water quality targets in large, multi-land use catchments will challenge our current knowledge base and the tools available.

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