

## Soil structural degradation in SW England and its impact on surface-water runoff generation

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### Abstract

Field investigations between 2002 and 2011 identified soil structural degradation to be widespread in SW England with 38% of the 3243 surveyed sites having sufficiently degraded soil structure to produce observable features of enhanced surface-water runoff within the landscape. Soil under arable crops often had high or severe levels of structural degradation. Late-harvested crops such as maize had the most damaged soil where 75% of sites were found to have degraded structure generating enhanced surface-water runoff. Soil erosion in these crops was found at over one in five sites. A tendency for the establishment of winter cereals in late autumn in the South West also often resulted in damaged soil where degraded structure and enhanced surface-water runoff were found in three of every five cereal fields. Remedial actions to improve soil structure are either not being undertaken or are being unsuccessfully used. *Brown Sands*, *Brown Earths* and loamy *Stagnogley Soils* were the most frequently damaged soils. The intensive use of well-drained, high quality sandy and coarse loamy soils has led to soil structural damage resulting in enhanced surface-water runoff from fields that should naturally absorb winter rain. Surface water pollution, localized flooding and reduced winter recharge rates to aquifers result from this damage. Chalk and limestone landscapes on the other hand show little evidence of serious soil structural degradation and <20% of fields in these landscapes generate enhanced runoff.

**Keywords:** Soil structure, structural degradation, compaction, runoff generation, soil erosion, soil hydrology

### Introduction

Crop and stock management systems used in SW England have the potential to damage soil structure and to change the hydrological properties of soil. Soil damage is caused by compaction, smearing and capping, which markedly reduce vertical water movement through soil by reducing porosity, increasing density, coarsening soil structure, and in serious cases resulting in the formation of structureless massive layers. In extreme cases of compaction most rain water flows laterally above the zone of compaction, either across the soil surface or within upper soil layers, instead of infiltrating vertically into soil.

The adverse effects of soil compaction have been recognized for many years. Forty years ago, the Ministry of Agriculture,

Fisheries and Food produced a report *Modern Farming and the Soil* (HMSO, 1970), which provided clear evidence that land management was impacting adversely on soil structure. In conclusion, the report recommended that '*Farmers on the weaker structured soils need to know more of what lies below and how to deal with their fields when they misbehave. Reduction in organic matter and modern farming together call for a new approach to farming what was once "easy" land*'. Little appears to have changed during the last 40 yr.

Soil compaction can be identified and assessed in many different ways: by field investigation, including visual assessment (Batey & McKenzie, 2006) or by measuring bulk density, porosity or penetrometer resistance; by laboratory analysis of physical properties such as air capacity or from using the triaxial shear test; or by microscopic inspection of thin sections of soils to analyse soil fabrics.

This study presents the findings of 31 surveys carried out in SW England between 2002 and 2011 using rapid field

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assessment based on visual and manual examination of soil structure and relating this to observed surface-water runoff generation. The methodology is developed from a classification of soil structural degradation established by the National Soil Resources Institute (NSRI), Cranfield University (Holman *et al.*, 2001, 2003). Field methods closely follow standard assessments and terminology developed and used by the former Soil Survey of England and Wales and its successor organizations for the last 70 yr (Hodgson, 1997). These methods are strongly influenced by international experience as incorporated into United States Department of Agriculture documentation (USDA, 1962, 1993).

The link between the degree of structural degradation and propensity for surface-water runoff has not been tested by measuring volumes of overland flow in this study. However, this has been measured elsewhere as identified in a review by Godwin & Dresser (2003).

## Methods

### *Field investigations*

Between 2002 and 2011, 31 studies (Table 1) were made in 24 different catchments across SW England (Figure 1) assessing the degree of soil degradation in relation to surface-water runoff. For each study (Palmer, 2002, 2007),

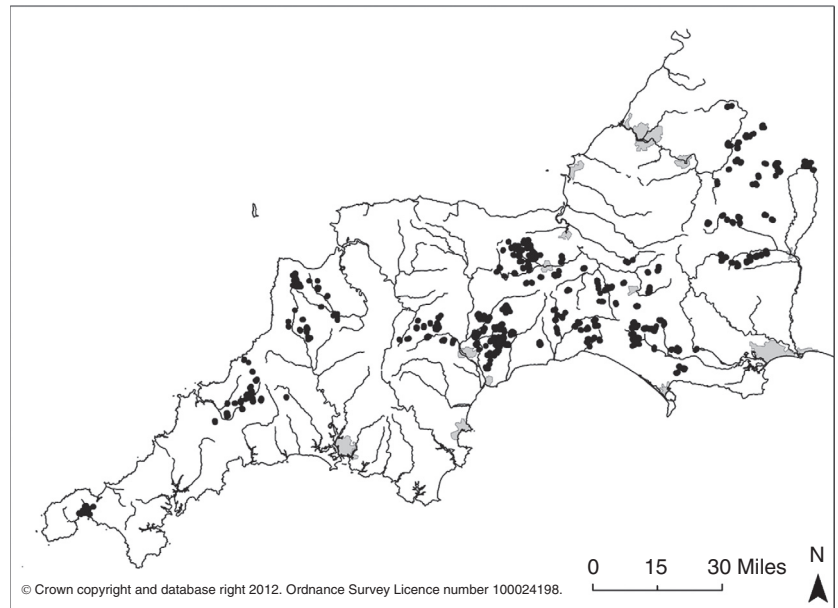
catchments were initially divided into broad soil landscape regions (Table 2), based on the 1:250 000 scale National Soil Map (NATMAP; SSEW, 1983). Flat alluvial and river terrace landscapes were not included in the surveys because surface-water runoff is limited in these landscapes.

A random selection of farms was initially identified within each soil landscape. For each farm, with the help of the farmer or land-owner, several pairs of fields were selected on the same soil type but each representing a different land use. Occasionally, where this selection process missed distinctive cropping systems, these were subsequently targeted. Latterly, comprehensive catchment surveys for Feniton (Palmer, 2009a), Thorne Farm (Palmer, 2009b) and Whimple (Palmer, 2010) have been included where every field in the catchment was assessed for structural degradation.

Soil structural assessment and diagnosis were always carried out during winter and early spring when soils were at or close to field capacity moisture content. This is the optimum moisture state for identifying soil structure in the field. If too wet (approaching saturation moisture content), soils easily slump when handled and natural structural units cannot be assessed. As soils dry in spring through summer to the autumn, while structural assessment is possible, it can be difficult to differentiate between artificial cracking introduced by the digging and sampling process and natural inherent fissures and structures in the soil.

**Table 1** Catchments studied

Catchment	Survey date	County	No. of observations
Tone	2002, 2003, 2006	Somerset	279
Parrett	2002, 2003, 2006	Somerset	260
Halsewater	2003, 2006	Somerset	249
Vale of Pewsey (Avon)	2003	Hampshire, Wiltshire	99
Wylfe (Avon)	2003	Hampshire, Wiltshire	54
Nadder (Avon)	2003	Hampshire, Wiltshire	78
Frome	2004	Dorset	240
Sem	2004	Hampshire	42
Marazion	2004	Cornwall	120
Camel	2005	Cornwall	142
Coly	2005	Devon	30
Torridge & Tamar	2008	Devon, Cornwall	188
Avon (Bristol)	2008	Wiltshire, Gloucestershire	159
Culm	2008	Devon	96
Yeo	2008	Devon	150
Axe and Char	2004, 2007	Devon, Dorset	282
Clyst	2008	Devon	45
Exe	2008	Devon	36
Clyst	2009, 2010	Devon	196
Feniton (Otter)	2010	Devon	80
Thorne Farm (Otter)	2010	Devon	94
Whimple (Clyst)	2010	Devon	252
Kentisbeare (Culm)	2011	Devon	72
Total	2002–2011	SW England	3243



**Figure 1** Location of catchment surveys in SW England.

**Table 2** Soil landscapes and associated soils

Broad soil landscape	Minor soil landscape	Soil associations or series
Chalk and Limestones	Chalk crests and scarps	Andover, Upton, Wantage, Panholes
	Chalk footslopes	Coombe, Soham, Blewbury
	Shallow, brashy limestone (Inferior Oolite, Cornbrash)	Elmton, Sherborne, Aberford
Light-textured soils	Triassic soft siltstone and sandstone lowland	Bromsgrove, North Newton, Bridgnorth, Cuckney
	Soft Lias siltstone and sandstone lowland	Yeld, Curtisden, Bridport, South Petherton
	Greensand	Bearsted, Urchfont, Ardington
	Thick Silty drifts	Fyfield, Charity
	Corallian ridges	Fyfield
Clay-rich soils	Golden Mile	Ludgvan – man made soils
	Clay vales	Wickham, Denchworth, Evesham
	Mercia Mudstones	Whimple, Worcester, Brockhurst
	Dunland clays (Culm Measures)	Hallsworth, Halstow, Dale, Bardsey
	Clay cap	Batcombe, Hornbeam, Carstens
Upland soils	Peaty Granite upland	Hexworthy
	Granite upland	Moretonhampstead
Medium-textured soils	Dunland (Culm Measures)	Neath, Sannan, Cherubeer
	Redland breccia hills	Crediton, Shaldon, Milford, Mercaston
	Devonian slate hills/Shillet	Denbigh, Manod

In each chosen field, three observation sites were identified in order that field assessments covered the main variations in soil type and crop growth in each field. In arable or grass fields with variable crop growth, a soil assessment was usually made in representative areas of good, poor and average crop growth. Where there were patches of wet ground, rutting in arable fields or poaching in grassland, some assessments were targeted in these areas to review whether these features indicate differences in soil structure or were related to changes in soil type.

#### *Site description, assessment and diagnosis*

At each site, the upper soil layers were inspected in a hexagonal-shaped pit with the sides the width of a spade and dug down to 40–50 cm depth. Care was taken to protect one of the six sides from compaction from the digging process. Slices of soil were excavated from the undisturbed side at 0–25 cm depth and then 25–50 cm depth. These two spits of soil were used for diagnosis of structural condition of undisturbed soil, both within the topsoil and in the critical

subsurface layers where compaction pans can develop. A 5-cm-wide Edelman 'dutch' auger was also used to inspect and describe the soil below the pit down to 1.2 m depth to classify (Avery, 1980) each soil and assign it to a soil series (Clayden & Hollis, 1987).

Structural units were described in terms of size, shape and degree of development. The strength of individual peds was assessed, as appropriate, by crushing an unconfined 3-cm cube of natural soil between extended thumb and extended forefinger, or between hands or pressing with the foot against a hard surface. There was often more than one structural type present in each soil horizon so topsoils (Ah or Ap horizons) often needed to be described as Ah1, Ah2, Ah3, etc. and structural changes logged. All assessments follow the terminology and classes of Hodgson (1997) and the following key soil features were assessed where relevant:-

*Surface condition.* The degree of surface slaking caused by rain impact and frost action breaking surface aggregation was recorded. This washing together, sorting and redistribution of surface particles often results in the formation of a surface cap on drying. These changes can seriously affect the natural infiltration capacity of the soil surface (NSRI, 2001).

*Wheelings and tramlines in the crop.* The depth of wheelings and tramlines in the crop was recorded. As the depth of wheelings increases, the possibility of structural damage increases.

*Extent and degree of poaching on grassland.* The depth and extent of surface irregularities were recorded, which in extreme cases produces puddled surfaces.

*Soil structure within the soil profile.* The definition of soil structure used here is that used by Hodgson (1997) and relates to – *the shape, size, degree of development of the aggregation, if any, of the primary soil particles into naturally or artificially formed structural units (peds, clods, artificial and natural fragments), and to the spatial arrangement of these units including the description of voids (pores and fissures) between and within the aggregates.* Structural change within and at the base of the topsoil and in the upper subsoil was recorded.

*Features of soil erosion and deposition.* Evidence of sheet, rill and gully erosion and build up of sand or laminated silt in hollows, adjacent to streams or upslope of hedges was recorded.

*Vertical wetness gradients within the soil profile.* In naturally well-drained, permeable soils in winter, the whole soil profile

shows a similar state of wetness throughout its depth, except for a short period after intense rainfall events. Structural degradation can be inferred when these soils have wet upper soil layers overlying significantly drier subsoils where compaction is identified in the zone of moisture change. In naturally slowly draining soils (especially surface-water gley soils), subsoils are slowly permeable with water movement after rainfall restricted to fissures and pores where continuous and joined. Structural units can be naturally dense and following rainfall, wet on the outside but dry internally. For some time after rain, the topsoil on these slowly draining soils can be wetter than their subsoils forming a natural vertical wetness gradient.

#### *Classification of soil structural degradation in relation to surface-water runoff*

To help comparison between sites and to provide a framework for interpretation of structural degradation in relation to runoff, a simple classification was used (Figure 2) based on work developed by Cranfield University (Holman *et al.*, 2001, 2003).

## Results





A total of 3243 soil structural assessments have been recorded within 31 catchments covering more than 50 soil associations in SW England. Thirty-eight per cent of sites (=1262 sites) had *High* or *Severe* levels of soil structural degradation, where enhanced surface-water runoff was being generated across whole fields. A further 50% of fields showed *Moderate* levels of degradation leading to localized patches of enhanced runoff. Just 10% of sites were assessed with *Low* levels of soil structural degradation, where there was insignificant surface-water runoff observed.

Structural damage under cultivated sites (including ley grass) was far more severe and widespread than under permanent grass (Figure 3). Over 55% of cultivated sites were associated with *High* or *Severe* levels of soil structural degradation whereas <10% of permanent grass sites were similarly damaged. Soils under ley grass had four times more *High* or *Severe* levels of degraded structure than under permanent grass (Figure 3).

Land where late-harvested crops had been grown, such as maize and potatoes, was the most damaged, with about 75% of sites showing *High* or *Severe* levels of soil structural degradation (Figure 3). Over one in five of these sites had signs of overland flow in the form of rill and gully erosion or depositional features. Winter cereal cropping also produced a large percentage of damaged soils where over 60% of sites had *High* or *Severe* levels of soil structural degradation.

There was a strong contrast in structural degradation across the range of soil types found in SW England. Lime-



Soil Degradation class	Key soil and landscape features	Generation of surface-water runoff
Severe	<p>Extensive rills and gullies on slopes, and depositional fans on footslopes. Degraded soil structure either on the surface, topsoil, or upper subsoil layers.</p> 	Enhanced surface-water runoff across the whole of the field
High	<p>Capped surface soil; wheelings often &gt;5 cm deep; structural change in topsoil or immediate subsurface layer; compaction causing dense angular or platy structures, locally structureless-massive matrix; plough pans frequently present; abnormal vertical wetness gradients. Grasslands surfaces compacted by trampling or silage making; poaching often severe.</p> 	Enhanced surface-water runoff across the whole of the field indicated by wash lines, flattened crops and grass.
Moderate	<p>Cultivated fields often have slaked or partly slaked topsoils, some prominent wheelings (&lt;5 cm deep); localised compaction or weakening and coarsening of structure. Grassland usually poached (locally severe). Degraded subsoil structure.</p> 	Localised enhanced surface-water runoff restricted to parts of fields (e.g. tramlines and headlands).
Low	<p>Soil profile is well structured and typical of the texture and soil water regime of the soil series. Subsoils can be naturally dense, coarsely structured and slowly permeable.</p> 	Insignificant enhanced surface-water runoff generation. Infiltration into topsoils is adequate and through-flow in well structured upper horizons is sufficient to preclude surface-water runoff on slopes.

**Figure 2** Soil degradation classes and their link to surface-water runoff generation.

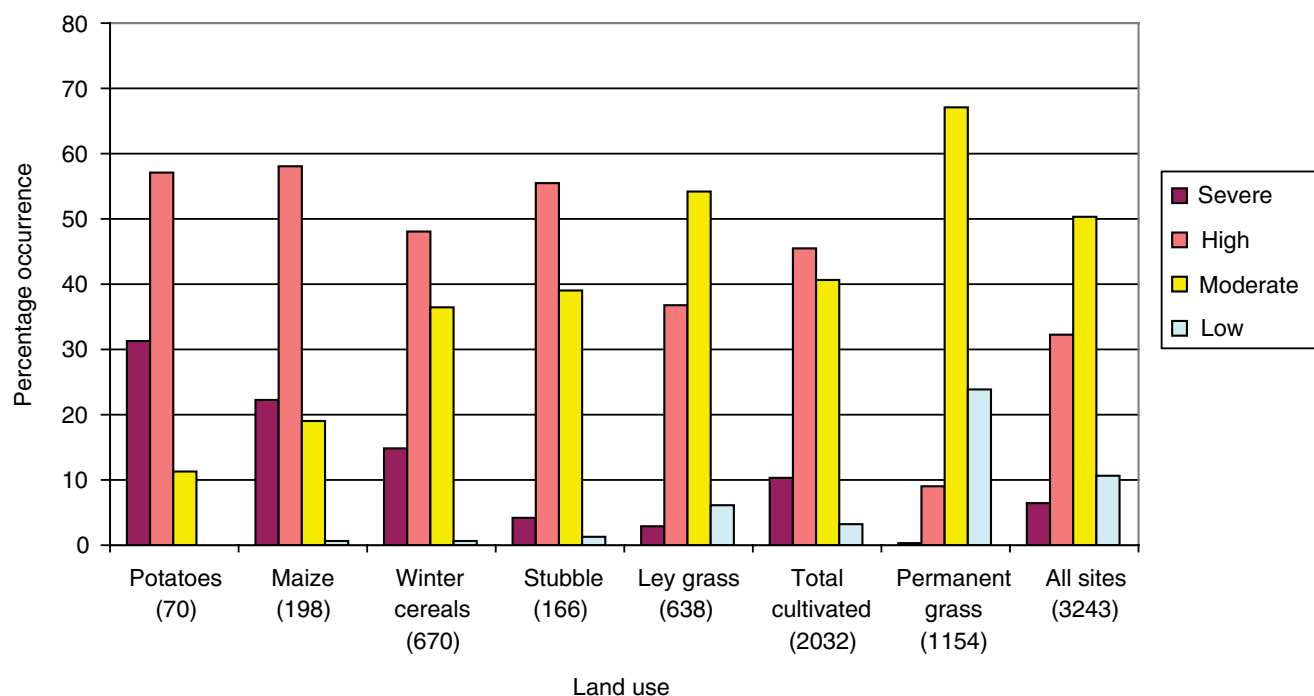
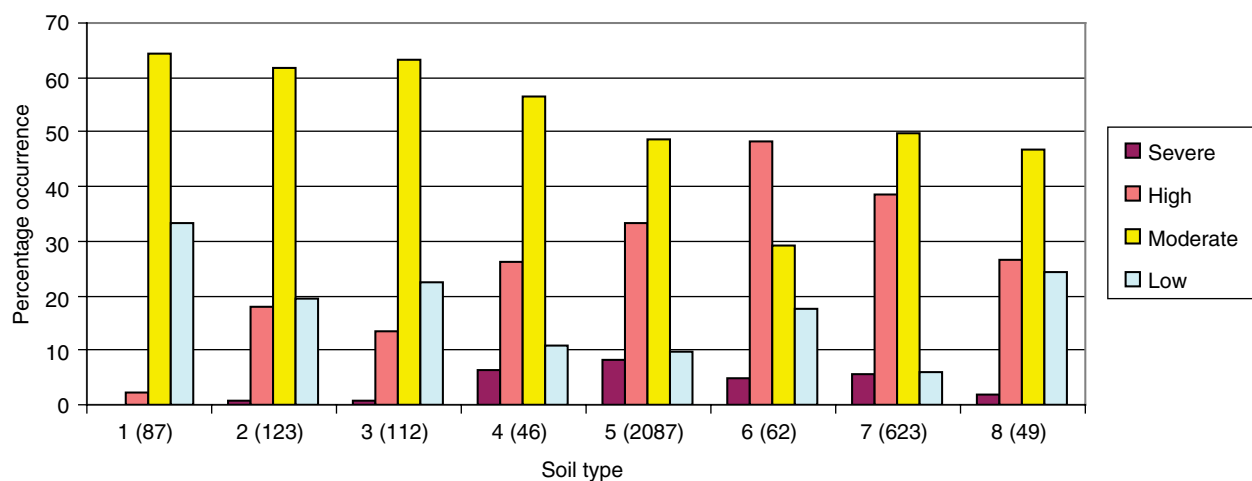


Figure 3 Degree of soil degradation under grassland and crops in SW England.



1 - Shallow over chalk/limestone;

2 - Medium to deep soils over chalk/limestone;

3 - Pelosols

4 - Brown Podzolics

5 - Brown Earths;

6 - Brown sands

7 - Surface water gleys

8 - Groundwater gleys

(87) – No. of sites

Figure 4 Degree of soil degradation for different soil types in SW England.

rich soils over chalk and limestone were the least degraded. Both shallow and deep calcareous soils (Groups 1 and 2 in Figure 4) had more than 80% of sites in reasonable structural condition (exhibiting *Low* and *Moderate* levels of degradation). Relatively well-drained clay soils (pelosols – Group 3 in Figure 4) were similarly undamaged. Brown sands were the most structurally degraded soil group (Group

6 in Figure 4). Over 53% of these sandy soils have *High* or *Severe* levels of soil structural degradation. Surface-water gley soils (Group 7 in Figure 4) and groundwater gley soils (Group 8 in Figure 4) were also found to be frequently degraded. *Severe* and *High* levels of degradation were reported from more than 45% and 30%, respectively, of these soils.

## Discussion

The surveys carried out in this study demonstrate widespread degraded soil structure in SW England causing enhanced surface-water runoff. Cultivated *Brown Sands*, *Brown Earths* and loamy *Stagnogley Soils* (Avery, 1980) were the most frequently damaged soils. These three groups of soils cover more than 50% of SW England (Findlay *et al.*, 1983) indicating the widespread potential for enhanced runoff in the South West.

Soil type, especially the texture of the whole soil profile, not just the topsoil, and soil water regime have a profound influence on the susceptibility of soils to compaction and structural damage. Shallow loamy soils over chalk, which are invariably stony and well drained, are resistant to compaction. Less than 20% of 210 observations in chalk and limestone landscapes were found to have *High* or *Severe* levels of degradation. Following structural damage, these carbonate-rich soils readily regenerate blocky or granular structure. It is likely that the presence of hard tabular stones in the topsoils also helps to increase bearing strength in these soils and minimize structural damage.

SW England is more vulnerable to soil structural damage than many other agricultural areas of the UK. Rainfall is much higher than Eastern England, for example, with more frequent episodes of intense rainfall. Many of the agricultural areas of SW England are more strongly sloping than typical of Eastern or Midland England. Furthermore, much of the cropping in SW England carries a high risk of damaging soil structure in this high rainfall area, including maize, ley grass, winter cereals and vegetables.

O'Connell *et al.* (2004), review the impact of rural land management on flood generation and conclude that there was substantial evidence that changes in land use and land management practices affect surface-water runoff generation at the local scale. Similarly, Boardman *et al.* (2006) have provided a comprehensive review of soil erosion in Europe including the generation of 'muddy floods'. Archer *et al.* (2010) demonstrate a link between land use and floods at catchment scale. They show from studies in the Axe catchment in Devon that rates of change in discharge volume respond to land use change at both the small and large catchment levels. The clearest evidence for this relationship was for moderate floods resulting from rainfall events of 10–30 mm/day.

Degraded soil structure and enhanced surface-water runoff have a high risk of causing water pollution where runoff transports fine sediment, organic material, crop nutrients, pesticides and microbes. The EU Water Framework Directive (European Parliament, 2000) requires all countries throughout the European Union to manage the water environment to consistent standards. This Directive introduces a 6-yr cycle for river basin management plans aimed at improving the water environment. In the first SW

River Basin Management Plan in 2009, only 33% of surface waters were classified as good or better ecological status (EA, 2009). The first cycle of river basin management planning has set a challenging objective whereby 42% of surface waters will be at good or better ecological status/potential by 2015. To achieve this target, it is very likely that soil management will need to be improved.

Permeable, well-drained sandy and sandy loam soils overlying aquifer bedrocks such as the Bridgnorth, Bromsgrove and Bearsted associations (Findlay *et al.*, 1984) are often susceptible to soil structural damage. Locally, compaction damage leads to the rapid shedding of winter rainfall laterally to watercourses instead of its normal steady infiltration into these soils. Winter recharge to underlying aquifers can be lost causing a steady decline in groundwater levels. Hess *et al.* (2010) modelled the impacts of soil structural degradation on percolation, recharge and baseflow in rivers and demonstrate, that improvements in agricultural soil/field condition produced modest simulated increases of up to 10% in the indicative Base Flow Index (Boorman *et al.*, 1995) in most catchments across England and Wales.

A range of mechanical methods are available to improve damaged structure (Spoor, 2006), including topsoil lifting, ploughing and subsoiling depending on the degree of damage and where it occurs in the soil profile. Clements & Donaldson (2002) demonstrated that overland flow could be dramatically reduced by improving the structure of overwintered maize stubble fields. In some cases, certain crops should not be grown on high-risk soils (e.g. maize on stagnogley soils adjacent to watercourses). Slurry and manure spreading should also be avoided when the soil is too wet, often leading to the necessity for 5–6 months storage. Wherever livestock are out-wintered, care is needed in choosing fields with a low risk of structural damage and runoff, and even so these soils are likely to need subsequent loosening of upper topsoils to alleviate inevitable compaction damage at shallow depth.

The Environment Agency has a programme of catchment studies to identify runoff problems and is working with partners, farmers and their advisers to deal with these problems. In East Devon, the Environment Agency funded a project where a subsoiler was purchased and made available to a local contractor who provided a subsidized service to farmers to deal with soil compaction identified by soil surveys. Sites were revisited after treatment and about 50% of these were found to be improved (Palmer, 2011).

The Catchment Sensitive Farming and Soils for Profit projects in SW England, funded by Defra, have been providing advice and training events to raise awareness of the need to improve soil management to deal with the consequences of enhanced runoff. Future soil structure surveys will be needed to determine the success of these

schemes. Most of the Environment Agency and Government funded work that addresses runoff from agricultural land is currently advisory in nature and there are numerous guidance booklets available (EA, 2008). However, in cases where severe runoff has caused 'point source' sediment pollution, the Environment Agency has taken legal action with farmers using its control of pollution powers by applying 'The Environmental Permitting (England and Wales) Regulations 2010'.

Improving soil structure should benefit farming in the SW by retaining input fertilizers within the soil rather than these being washed away by overland flow. Better soil structure will improve the depth of crop rooting and provide a more reliable supply of water for plant growth (Soane *et al.*, 1987). Farmers are becoming aware of the linkage between soil structural degradation and runoff generation, and it is in their own interests to improve soil condition where they can. The Maize Growers Association has led a successful campaign in partnership with the Environment Agency to improve the management of soil under maize. New early maturing maize varieties are being widely adopted, and frequently now maize stubble is being rough cultivated in autumn to remove topsoil compaction and surface damage.

## Conclusions

This study is the first time in SW England that an extensive survey of soil structural degradation has been linked to the generation of enhanced surface-water runoff. The survey demonstrates that degradation occurs under many cropping systems with significant implications for the environment as enhanced runoff can cause water pollution and localized flooding and reduces groundwater recharge through some soil types.

The field-based method of soil structure assessment is relatively quick and cheap to carry out with each observation taking between 10 and 15 min and a field diagnosis of structural damage and any necessary remedial actions can be identified in less than an hour. It is important that farmers and advisers become proficient in identifying soil structural condition and that assessments become part of routine soil management on the farm.

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