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Review

Crop residue mulching in tropical and semi-tropical countries: An evaluation of residue availability and other technological implications

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Abstract

Crop residue mulching (CRM) can be defined as a technology whereby at the time of crop emergence at least 30% of the soil surface is covered by organic residue of the previous crop. The present study proposes CRM as the most adequate term for the technology in view of the substantial controversy and confusion surrounding existing terms, particularly conservation tillage. CRM is a dual-purpose technology that combines conservation and productivity effects. Its conservation potential hinges on the presence of the crop residues as mulch. This mulch provides a protective layer to the soil surface that is extremely effective in halting soil erosion and also amends the soil ecology. Its productivity potential is twofold. First, the mulch tends to stabilise, and occasionally even enhance, crop yield. Second, it implies factor substitution and input use efficiency alterations.

The paper presents the residue balance as an analytical tool to assess the current availability of residues—both in terms of current residue production and current residue destinations. Residue destinations typically include extraction, burning in situ, incorporation, weathering and retention as mulch. CRM has profound implications for crop management. First, CRM implies a set of necessary practices so as to ensure the retention of sufficient residues as mulch. Second, CRM may imply complementary adaptations in order to be able to grow a crop and/or maintain productivity levels. Therefore, CRM is not a simple add-on technology, but instead a complete package of cultural practices. The actual potential of the CRM technology depends on a comprehensive assessment of the socio-economic implications of the implied changes. This potential is site-specific and will diverge between the private and social viewpoint. CRM therefore is a promising dual-purpose technology—but no panacea for soil conservation in (semi-)tropical countries.

Keywords: Conservation farming; Mulching; Conservation tillage; Tropical and semi-tropical countries; Technology assessment; Crop residues

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1. Introduction

Arable farming with the retention of crop residues as mulch—commonly known as conservation tillage—has made a significant advent in the USA, comprising more than 35% of the cropped land since the mid-1990s (CTIC, 2000). The distinguishing and novel feature of these tillage systems is the retention of a crop residue mulch just after crop establishment to ensure an adequate soil cover. These systems are revolutionary as over the centuries agriculture has traditionally emphasised the opposite, i.e. the need for a clean seedbed without crop residues. Numerous farmers in developing countries still rely on pre-plant burning of vegetative debris for this purpose. So, have farmers in developed countries in the past. However, with the advent of tillage opportunities over the last

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two centuries, incorporation of residues provided an alternative. Tillage also provided other benefits, including weed control and the creation of a favourable environment for crop sowing and emergence (e.g. Kuipers, 1991; Hoogmoed, 1999). Both tillage and burning practices conflict directly with the retention of crop residues as mulch. Indeed, the retention of mulch actually requires relatively little or no disturbance of the soil and the elimination of burning. The difficulty has been how to economically achieve this.

The discovery and commercial development of herbicides provided part of the solution. During the WW II, post-emergence herbicides were discovered (2,4-D and MCPA). Other herbicides followed in the 1950–1960s—including triazines and ureas (Rijn, 1982; Violic, 1989a). With time, herbicides increasingly provided an economic substitute for the weed control function of tillage (Unger, 1990). Another crucial component for mechanised agriculture was the development in the post-war years of planting equipment (direct seed drills) that could adequately sow through the mulch (Phillips, 1983; Violic, 1989b). Both the herbicides and planting equipment allowed for the successful establishment of crops while retaining a mulch. With further fine-tuning of the technology and favourable market developments, such systems became an increasingly attractive economic alternative for crop production on well-drained soils in the USA from the 1970s onward (Allmaras and Dowdy, 1985). The USA is generally perceived to be the cradle of this technology—with a large body of literature to document the advances of research and its use (Phillips and Young, 1973; Triplett and van Doren, 1977; Phillips et al., 1980; Phillips and Phillips, 1983; Rice, 1983; d'Itri, 1985; Sprague and Triplett, 1986; Carter, 1994; Hatfield and Stewart, 1994; Unger, 1994).

The success of the technology in the USA has generated substantial interest to replicate such conservation farming systems elsewhere. The practice of retaining crop residues as mulch is indeed increasingly reported from various corners of the world (Unger and McCalla, 1980; Rijn, 1982; Wiese, 1983; Shear, 1985; Watson and Allen, 1985; Cornish et al., 1987; Lal, 1989; Unger, 1990; Freebairn et al., 1993; Cannell and Hawes, 1994; Derpsch, 1998; Koller et al., 1998; Wall, 1998; Erenstein, 1999a). However, advances outside the USA have been mixed and less significant. This calls for a closer look at the technology and its appropriateness outside its American base—particularly in (semi-)tropical countries.

The current paper evaluates five basic issues of the use of crop residues as mulch, with a particular emphasis upon (semi-)tropical developing countries. First, the paper reviews the definition of this technology. Second, the paper summarises the main technological effects—particularly in terms of the implications for soil conservation and productivity. Third, the paper introduces the crop residue balance—an analytical tool for crop residue mulching (CRM) which equates crop residue production with utilisation. Fourth, the paper reviews the management implications for adopting the technology—both in terms of adapting the residue balance (necessary practices) and other crop management (complementary practices). Fifth, the paper reviews the need to provide a comprehensive socio-economic assessment of the technology. Each issue is reviewed in a separate section. The paper ends with a concluding section.

2. Definition of CRM

CRM can be defined as a technology whereby at the time of crop emergence at least 30% of the soil surface is covered by organic residue of the previous crop. The timing aspect relates to the limited crop cover at the onset of the season—and the correspondingly high erodibility of the soil. The 30% threshold originated in the USA (Allmaras and Dowdy, 1985) but is rather arbitrary and higher levels of soil cover imply even greater reductions of soil erosion. The reliance on organic residues from the previous crop distinguishes CRM from other forms of mulching (Erenstein, 1999a).

CRM is better known as 'conservation tillage'. However, there is substantial controversy and confusion around this latter term. Several factors have contributed to this. A first confounding factor is that various definitions of conservation tillage exist and these have changed over time (Pierce, 1985). Early definitions tend to be more abstract and emphasise tillage and relative erosion (SCSA, 1982; Mannering and Fenster, 1983; Violic, 1989b). Current definitions are more operational and tend to emphasise the soil cover threshold of 30% (Lal et al., 1990; CTIC, 2000). Some authors use or cite both the abstract and operational definition (Unger, 1990; Allmaras et al., 1991; Figueroa and Morales, 1992; Carter, 1994).

A second confounding factor is that conservation tillage is a generic umbrella term that includes several tillage practices and systems (Mannering and Fenster, 1983; Lal, 1989; Carter, 1994; CTIC, 2000). Consequently, it is variously interpreted depending on which subset is emphasised (e.g. Dickey et al., 1987; Gould et al., 1989; Lee and Stewart, 1983, 1985; Heimlich, 1985).

A third confounding factor are the terms 'conservation' and 'tillage' themselves. 'Conservation' is variously interpreted (Conservation of what? Of soil, water, crop residues?), whereas numerous types of 'tillage' exist—with some tillage terms (partially) overlapping and occasionally used interchangeably (Mannering and Fenster, 1983). The inclusion of 'tillage' in the technology name also puts too much emphasis on physical soil tillage. This seems adequate in the mechanised production systems of the USA, where the term originated. There, incorporation through tillage was the principal destination of the residues (Sandretto and Bull, 1996). Reducing tillage typically implied substantial quantities of residues remained as mulch (Heimlich, 1985). However, in (semi-)tropical countries, tillage is only one of the various factors that determines residue availability as mulch. What is more, in many production systems in developing countries there is traditionally no tillage at all (Akobundu, 1987).The controversy and confusion over conservation tillage is particularly problematic to its advance in the developing countries, where language barriers and resource constraints add in their toll. Indeed, the limited information available on conservation tillage in developing countries needs to be interpreted with care in view of the varying interpretations.

To circumvent the conservation tillage controversy other names have surfaced. A number of alternatives still emphasise the tillage aspect—e.g. no till; minimum till; direct sowing—with the consequent confusion and potential neglect of the mulch aspect. Other definitions are wider and tend to see mulch as implicit—e.g. land husbandry (Shaxson et al., 1989; Hudson, 1992; Hudson and Cheatle, 1993) and conservation farming (Moldenhauer and Hudson, 1988; Wijerwardene and Waidyanatha, 1989; Moldenhauer et al., 1991). Crop residue management has also been suggested as an alternative (SWCS, 1991; Hatfield and Stewart, 1994; Moldenhauer et al., 1994; Sandretto and Bull, 1996; CTIC, 2000) and refers to a year-round system that includes all field operations that affect the amount of residue (Sandretto and Bull, 1996; CTIC, 2000). It correctly emphasises crop residues. The problem though remains that it is unspecified: it simply is too broad. Indeed, all practices affecting residues are forms of management and some of these may not be compatible with the retention of residues as mulch (Cornish et al., 1987; Erenstein, 1997). In addition, crop residue management has already been variously defined (e.g. CTIC, 2000).

The alternatives put forward do not fully resolve the controversy and confusion surrounding conservation tillage. The present paper and Erenstein (1999b) therefore propose CRM as the most adequate term for the technology. It is less confounded by controversy and correctly emphasises the pertinent issues—i.e. the presence of a mulch and its origin.

3. Conservation and productivity effects of CRM

A crop residue mulch is strategically located at the soil-atmosphere interface, whereby it affects: (i) soil conservation; (ii) soil ecology; (iii) crop yield; (iv) labour and capital productivity; and (v) agricultural externalities.

3.1. Soil conservation effects

A crop residue mulch effectively halts soil erosion by providing a protective layer to the soil surface, increasing resistance against overland flow and enhancing soil surface aggregate stability and permeability through its combined physical and biological effects (Fig. 1). The resulting reduction in soil erosion is impressive (e.g. Table 1) and has been repeatedly observed both in temperate and tropical environments (Shaxson et al., 1989; Lal et al., 1990; Alegre et al., 1991; Khybri, 1991; Langdale et al., 1994; Moldenhauer et al., 1994; Stocking, 1994). Erosion declines asymptotically to zero as cover increases. A near complete soil cover can conceivably almost eliminate soil erosion (Quadrant I of Fig. 2; Lal et al., 1990; Moldenhauer et al., 1994). Although larger

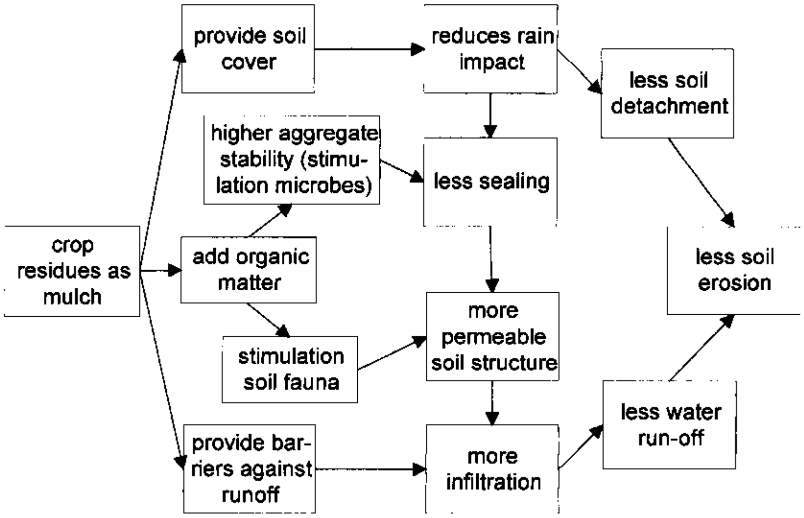

Fig. 1. The soil conservation effect of CRM.

Table 1
Mulch effects in Zimbabwe (on-station trials, average 1988–1995)[a]

	Domboshawa (758 mm annual rainfall)				Makoholi (463 mm)	
	Well-drained soil		Poor-drained soil		Clean till	Mulch till
	Clean till	Mulch till	Clean till	Mulch till		
Maize yield ($Mg\,ha^{-1}$)	3.2	4.0	3.1	3.0	2.9	3.6
Runoff (mm)	71	15	109	46	54	14
Soil loss ($Mg\,ha^{-1}$)	5.3	1.0	6.1	1.0	9.6	0.9

[a] Source: various sources in Elwell (1995).

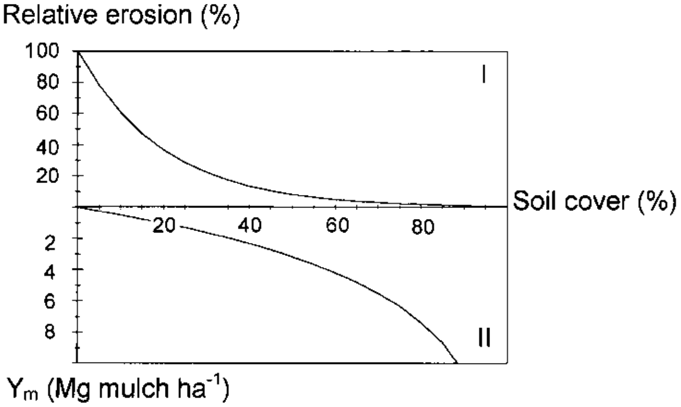

Fig. 2. Two-quadrant graph showing the hypothetical relationship between relative erosion and soil cover in Quadrant I; and soil cover and amount of mulch [Y_m] in Quadrant II (Erenstein, 1999b).

Table 2
Effects of variable mulch rates on water and soil loss in Nigeria (forest–savanna transition zone, April–October 1977)[a]

Mulch rates (Mg rice straw per hectare)	Runoff (%)	Soil loss ($\mathrm{Mg\,ha^{-1}}$)	Marginal conservation effect (Mg soil) $(\mathrm{Mg\ mulch})^{-1}$
0	75.4	9.6	
2	43.4	2.3	3.7
3	15.2	0.5	1.8
6	5.4	0.1	0.13
12	0	0	0.017

[a] Source: De Vleeschauwer et al., 1980 in Carsky et al., 1998.

amounts of residues do conserve soil better, increasing quantities of residue are required for additional improvements in soil conservation (Table 2; Quadrant II of Fig. 2; Allmaras et al., 1985; Kok and Thien, 1994).

3.2. *Soil ecology effects*

The presence of a crop residue mulch at the soil–atmosphere interface alters the entire soil ecology (Lal, 1989; Carsky et al., 1998). CRM has a profound water conserving effect: the very process that conserves the soil also implies more infiltration of rain water and less runoff (Fig. 1, Tables 1 and 2) and more water is retained in the soil profile (Featherstone et al., 1991; Dalrymple et al., 1992; Moldenhauer et al., 1994). The presence of the mulch also reduces soil temperature oscillations and reduces evaporation losses. CRM also has profound effects on soil fertility. Tropical soils typically have a low inherent fertility, where plant available nutrients and organic matter are concentrated in the topsoil. The conservation effect of mulch helps maintain this in situ, whereas the mulch itself typically adds to the low stock of soil organic matter—a key component for sustainable and productive use of soils (Pieri, 1989). CRM favours the activity of soil biota by providing a readily available food source and creating a more favourable soil habitat (Mando, 1997; Carsky et al., 1998). In turn, the activity of soil biota contributes to improved soil physical and chemical properties.

3.3. *Crop yield effects*

The growth of plants is primarily a function of: (i) defining conditions (carbon dioxide; radiation; temperature; crop attributes); (ii) limiting conditions (water and nutrients) and (iii) reducing conditions (weeds; pests; diseases; pollutants—Rabbinge and van Ittersum, 1994). By changing the soil ecology, CRM affects a number of these biophysical conditions (Rijn, 1982; Lal, 1989; Unger, 1990). The marginal yield effect will depend on the extent these changes influence the constraint(s) for crop growth. This makes the yield effect of CRM crop-specific (Akobundu, 1987; Howeler et al., 1993) and site-specific—and somewhat difficult to disentangle in view of the numerous interactions (Lal et al., 1990; Sandretto and Bull, 1996).

The water conserving effect of CRM can induce a substantial yield increase when drought stress is an issue (Shaxson et al., 1989). But the same effect can actually be detrimental when it exacerbates poor drainage and water logging conditions (Rice, 1983; Lal et al., 1990; Table 1). In most instances, though, the water conserving effect may have little tangible effect on short-term yields in "normal" years. However, it will be particularly beneficial in dry years (Rijn, 1982; Thomas et al., 1983; Lal, 1989; Violic et al., 1989; Pierce and Lal, 1994)—with the important benefit of reducing productive risk and yield oscillations.

The organic matter contributed by CRM can have different short-term yield implications, typically hinging on the quality of that organic matter as reflected by the C:N-ratio. CRM also affects the incidence of crop weeds, pests and diseases. However, the yield effect is uncertain as many weeds, pests and diseases respond uniquely to the CRM-induced alterations in the crop–soil ecosystem (Forcella et al., 1994). Mulch also shields the soil surface against solar radiation, thereby buffering soil temperature fluctuations. This can alleviate soil temperature stress in the warmer environments, yet at the same time slows the necessary warming up of the soil in cooler environments (Rijn, 1982; Lal et al., 1990).

The short-term yield effect is therefore variable over space and time-depending on the mulch, crop and site-specific characteristics. Experiences so far have highlighted positive, neutral and negative short-term yield responses to CRM. Over time, the yield effects tend to be neutral to positive (Logan et al., 1991; Kapusta et al., 1996). Indeed, some productive benefits accumulate over time as mulching arrests soil degradation processes and gradually improves the soil in biological, chemical and physical terms.

3.4. *Labour and capital productivity effects*

CRM typically implies a major overhaul of crop management practices in order to maintain the mulch and to be able to grow a crop and/or maintain productivity levels. This can inherently alter the crop production technology, with two major effects for labour and capital productivity. First, mulching may alter factor requirements in view of the new practices and/or factor substitution. Second, mulching may alter input use efficiency by affecting the inputs' mode of application, mode of action, and/or effective loss. The retention of mulch directly affects the mode of application—for instance, by limiting the available options, or by making the application process itself less efficient. The altered soil ecology can affect the mode of action of the input. Mulching also affects the effective loss of applied inputs through runoff, leaching and volatilisation. The implications for labour and capital productivity are to a large extent dependent on the actual production technology and thereby site-specific. Depending on the situation, the net effects can be positive or negative for overall factor productivity.

3.5. *Agricultural externalities*

CRM potentially redresses a number of the negative externalities traditionally associated with agriculture. Most obvious is CRM's ability to halt human-induced soil erosion in agriculture—thereby retaining the productive capacity on-site and reducing the generally adverse off-site impacts of eroded sediment and soil erosion related pollutants. CRM also implies C-sequestration through the temporary immobilisation of CO_2—a green-house gas contributing to global warming—by maintaining the crop residues on the soil surface. CRM thereby can convert annual cropping from a net source of CO_2 to a net sink (Kern and Johnson, 1993). CRM also implies more water infiltration and less runoff from agricultural land, thereby smoothing the downstream hydrological cycle and refilling acquifers. CRM is typically water conserving and thereby tends to stabilise yields in drought-prone environments—reducing national food production risks and enhancing food security. CRM can also aid in the sedentarisation of itinerant agriculture, thereby reducing existing pressures on fragile ecosystems.

4. The residue balance—an analytical tool for CRM

CRM requires the retention of sufficient residues as mulch after crop establishment. Yet in (semi-)tropical country agriculture, limited residues typically remain as mulch after crop establishment. Therefore a first analytical step should assess the current availability of residues—both in terms of current residue production and current residue destinations. An analytical tool to this effect is the residue balance (Erenstein, 1999b). This is the physical balance of residues for a specific location, equating residue production with aggregate residue use. For a specific location, the residue balance may be expressed as:

$$P = U_E + U_B + U_I + U_W + U_M \qquad (1)$$

where P is the production of residues and each U a specific use of residues (U_E: residues extracted; U_B: residues burned in situ; U_I: residues incorporated; U_W: residues lost due to weathering; U_M: residues retained as mulch). Both production and use are expressed as $\mathrm{Mg\,ha^{-1}}$. The various components of the residue balance are subsequently presented.

4.1. *Residue production*

Crop residue production is basically a function of: (i) biomass production; and (ii) the harvest index. Crop biomass production is determined by the biophysical environment, including defining, limiting and reducing conditions (Rabbinge and van Ittersum, 1994). Crop attributes are an important defining condition (e.g. a cereal crop potentially produces more biomass than a leguminous crop). Agronomic practices may alleviate limiting and reducing conditions through yield increasing and yield protecting measures, respectively (ibid). Socio-economic variables largely determine the actual use of such practices.

The harvest index expresses the agricultural commodity yield as a fraction of total (above-ground) crop biomass. The remaining biomass is generally perceived as a by-product and typically remains in the field as crop residue. The harvest index for cereals such as maize (*Zea mays*) is relatively constant for a given variety, but does vary greatly among crop varieties (e.g. 30% for a landrace and 50% for an improved variety). Thus, for a given level of biomass production, residue production will generally be substantially higher with a landrace than with an improved variety.

The production of crop residues ignores the potential contribution of weeds. However, weeds can occasionally provide a substantial contribution to annual biomass production. This may particularly underestimate actual organic residue production (i.e. crop and weed) in less intensive crop production systems (e.g. when weed control is incomplete and/or crop biomass production is limited).

4.2. Residue extraction

Crop residues are generally considered as agricultural by-products. However, in (semi-)tropical countries they have several productive uses and frequently are important sources of fodder, fuel, and/or construction material (Rijn, 1982; Bolton, 1991; Ofori, 1991; Unger et al., 1991; McIntire et al., 1992; Renard, 1997). Such uses are reported for various regions, including Africa, Asia and Latin America (Erenstein, 1999b). The intensive use of crop residues in developing countries is in contrast with developed nations, where they generally have few economic uses (Heimlich, 1985; Cannell and Hawes, 1994). The relative importance of each use varies geographically and by crop, as does the degree of extraction. Residue use as fuel or construction material involves the harvest of residues—i.e. the physical export of these from the field. Residue use as fodder may involve (stubble) grazing or actual harvesting for later use. In general, when done, the harvest of residues is thorough, leaving little in the field.

4.3. Residue burning in situ

Crop residues may be burned in situ prior to planting by the farmer or a third party—either intentionally or accidentally. Reasons for intentional burning include land clearing, fertility enhancement, weed/pest management, pasture management, hunting and personal well-being (Erenstein, 1999a). The first three are particularly relevant for CRM. Burning traditionally provides a fast way to clear the agricultural field of residual biomass and thereby facilitates further land preparation and planting (Akobundu, 1987). Burning is also perceived to boost soil fertility—although burning actually has a differential impact on soil fertility. It increases the short-term availability of some nutrients (e.g. P and K) and reduces soil acidity, but leads to a loss of other nutrients (e.g. N and S) and organic matter (Akobundu, 1987). It also provides a fast way of controlling various weeds, pests and diseases, both by eliminating them directly as by altering their natural habitat (e.g. mulch as hide-out for snakes and rodents—Akobundu, 1987; Thurston, 1992; Ravnborg et al., 1996). Burning is still widespread in developing countries. It also was a traditional practice in the developed countries (Bolton, 1991; Felton et al., 1987), but has increasingly disappeared. In some European countries, burning of residues is now illegal (Cannell and Hawes, 1994). In general, burning can be very effective for disposing of residues. However, it may be less effective when residue humidity is high or when there are limited or unevenly distributed residues (causing a non-uniform burn).

4.4. Residue incorporation

Physical tillage before planting is a common form of land preparation on arable land—i.e. on land fit for (semi-)mechanised tillage. The main purpose of land preparation is to create a clean, uniform seedbed that facilitates crop establishment. To achieve this, the topsoil is typically inverted, thereby incorporating the residues remaining on the soil surface. The degree of incorporation varies over tillage systems—depending on such issues as implements, intensity and mechanisation level (manual, animal traction or mechanised). Some tools have been developed to estimate potential incorporation in mechanised systems (CTIC, 2001; Kok and Thien, 1994).

4.5. Residue weathering

Even if not used for any specific purpose, the amount of residues diminishes over time due to weathering (CTIC, 2001)—encompassing both natural decomposition and removal by natural elements. Residue decomposition is largely a function of ecological factors (moisture, temperature, and biological activity) and the nature of the residues (fragility, C:N-ratio). Residue removal by water and/or wind can be important in areas with steep slopes and/or strong winds. Weathering is a year-round on-going process, but the interval between harvest and the

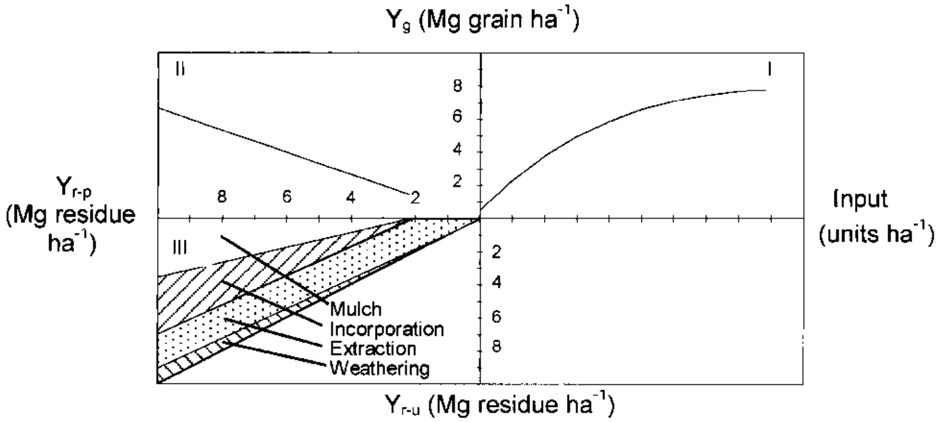

Fig. 3. Three-quadrant graph showing the hypothetical relationship between input use and grain yield [Y_g] in Quadrant I; grain and residue production [$Y_{r\text{-}p}$] in Quadrant II; and residue production and residue use [$Y_{r\text{-}u}$] in Quadrant III (adapted from Sain, 1996).

establishment of the subsequent crop is particularly relevant for CRM. Weathering is also more obvious in-between growing seasons as it is less masked by continuing biomass production. Weathering rates are largely exogenous, but can be substantial and may largely eliminate existing crop residues—e.g. in areas with high termite activity (Rijn, 1982; Thomas, 1988; Mando, 1997) and/or prolonged exposure between growing seasons.

4.6. Residue retention as mulch

The amount of residues that is retained as mulch depends on the residue production and other residue destinations. Mulching can therefore be seen as the residual claimant—i.e. it is formed with the residues that are left over after the other uses. In developing country agriculture, the amount of residues that are retained as mulch after crop establishment are typically limited.

Most residue uses (with the exception of mulching) are irreversible, exclusive, and therefore dependent on the chronological order. For example, if burning has eliminated most residues, subsequent incorporation during ploughing will be minimal. However, in case of not burning, incorporation could be substantial—ceteris paribus.

Fig. 3 illustrates some of the above relationships for a hypothetical case with a cereal crop. The first two quadrants depict crop residue production in response to input use. It uses a standard production function (yield – input) as starting point in Quadrant I. The form of the production function is determined by biophysical factors and reflects the product of biomass production and harvest index. Quadrant II links grain [Y_g] and residue production [$Y_{r\text{-}p}$]—assumed here to be a linear transformation based on a constant harvest index. Quadrant III depicts the residue balance—equating residue production [$Y_{r\text{-}p}$] with residue use [$Y_{r\text{-}u}$]. The fictive situation depicted assumes a harvest index of 40%, absence of burning, a 10% weathering index, residue extraction by grazing of up to 2 Mg ha^{-1} (either 2 or 0.9[$Y_{r\text{-}p}$], whichever is smaller) and reduced tillage with a 50% incorporation index.

5. Crop management implications of CRM

The implications of CRM on crop management are twofold (Erenstein, 1999b). First, CRM implies a set of necessary practices so as to ensure the retention of sufficient residues as mulch. Second, CRM may imply complementary adaptations in order to be able to grow a crop and/or maintain productivity levels.

5.1. Necessary practices for CRM

To ensure the retention of sufficient residues as mulch a set of necessary practices for CRM can be identified. The necessary practices follow from the residue balance (Eq. (1) above) and the fact that mulching is the residual claimant. Indeed, if a farmer wants to start retaining sufficient residues as mulch, he/she will have to adapt the other variables of the residue balance to make it compatible with CRM. Let U_M^* denote the amount of residues required to surpass the 30% soil cover threshold, which depends on crop, variety and residue management practices (e.g. in Meso America, U_M^* amounts to 2 Mg maize residue per hectare—Tripp and Barreto, 1993—but depends on the intensity of stubble grazing—Scopel and Chavez, 1996). The residue balance can therefore be reorganised into the following condition for CRM (using the same notation as Eq. (1)):

$$P - (U_E + U_B + U_I + U_W) > U_M^* \tag{2}$$

If this condition is satisfied at the time of crop emergence, sufficient residues are retained to qualify as CRM. If it is not, either residue production (P) will have to increase and/or its alternative uses (left-hand sum of U's) have to decrease in order to qualify as CRM.

Upon assessing the necessary changes, it is important to maintain a comprehensive residue balance perspective. Indeed, adapting individual components of the residue balance is typically insufficient. For instance, increasing in situ residue production is relatively futile as long as mulching remains the residual claimant and other uses (such as burning, incorporation and weathering) are a function of total biomass. Ceteris paribus, this implies that an increase in residue production would result in an increase in such uses. Furthermore, some of the residue uses are near perfect substitutes for each other in terms of eliminating residues. This is aptly illustrated by the zero till experience in the UK. During the 1970s, zero tillage for small grains became increasingly popular in the UK. However, zero tillage eliminates the possibility of residue incorporation, whereas small grains generate substantial amounts of residue, which when left as mulch increase wetness and make crop management more difficult. Most farmers therefore simply burned them (substituting burning for incorporation). Subsequent public environmental concern severely curtailed the possibilities of burning. Consequently, farmers reverted to incorporation—thereby practically eliminating zero tillage from the UK (Cannell and Hawes, 1994). The set of necessary conditions for CRM are subsequently presented.

5.1.1. *Limited incorporation*

The amount of residues incorporated during tillage should be limited. This is the case with zero tillage and to a lesser degree with reduced tillage. Ploughing is generally incompatible with CRM because it is so efficient in incorporating residues.

5.1.2. *No burning*

Residues should not be burned as residue management and/or land preparation practice. In some instances though, residue production is considered excessive and farmers prefer to maintain some form of residue elimination—e.g. wheat straw in Brazil (Castro et al., 1993). To circumvent the issue, the possibility of partial burning of residues is now contemplated as a CRM-compatible alternative in residue excess situations (Felton et al., 1987; Harris, 1996). For instance, in the Yaqui Valley of Northern Mexico partial burning of wheat straw is ensured by burning the residues in the early morning (high humidity) and prior to chopping (Harris, 1996).

5.1.3. *Limited extraction*

The amount of residues extracted as fodder, fuel and/or construction material should be limited. Intensive residue harvesting and/or grazing is generally incompatible with CRM.

5.1.4. *Limited weathering*

The amount of residues lost to weathering should be limited. Fragile residues and/or an 'aggressive' ecology (e.g. hot and humid; high levels of consumption by soil biota) may imply incompatible weathering losses. Weathering is difficult to reduce given that it is an autonomous process and a direct result of the forces of nature. The farmer can influence the weathering process somewhat—e.g. selecting a crop with non-fragile residues; using a non-destructive harvesting method; and limiting the time the residues are exposed to weathering (e.g. by altering the planting date). Weathering may increase when residues are left in situ (e.g. when it triggers an increase in termite activity—Mando, 1997).

5.1.5. Sufficient residue production

Residue production should be sufficient so as to be able to retain enough residues to surpass the 30%-cover threshold in the subsequent cycle. Marginal crop production conditions and/or crop characteristics may imply incompatible levels of residue production. For instance, in some semi-arid areas, levels of in situ residue production are so low that CRM appears doomed from the start (Unger et al., 1991). Conceivably, there is the option of importing sufficient residues into the field from an ex situ source—and this could be included in the residue balance by dis-aggregating the P-term to reflect in situ (P_I) and ex situ (P_E) production. In fact, farmers' use of cut-and-carry mulch for production agriculture has sporadically been reported (Reij, 1994; Slingerland and Masdawel, 1996). In general though, ex situ mulch is not economically feasible on a production scale for staple food crops (Akobundu, 1987; Lal, 1989; Baidu-Forson, 1994)—particularly in view of the substantial transporting and handling costs (Wilson and Akapa, 1983; Thurston, 1992).

The necessary conditions can be mirrored against the actual site-specific situation. Discrepancies thereby indicate the crop management adaptations needed to meet the necessary conditions for CRM—i.e. necessary for its adoption. The actual adaptations needed depend on the current location-specific practices and residue production. Most necessary practices follow directly from the necessary conditions and may include reducing tillage, eliminating burning and/or reducing extraction. The protection of residues may be a necessary practice whenever it is a third party that burns and/or extracts the residues (e.g. by maintaining a firebreak; by fencing the field; by chopping residues to make subsequent collection more difficult—Matthews, 1998). The feasibility of the different necessary practices varies—and some may inherently curtail the prospects of adopting CRM.

5.2. Complementary cultural practices for CRM

Necessary practices ensure the retention of sufficient residues as mulch. In turn, these changes may imply other complementary adaptations in order to be able to grow a crop and/or maintain productivity levels. Such complementary crop management practices may include adaptations to crop establishment and the management of nutrients, weeds, pests and diseases.

5.2.1. Crop establishment

CRM implies a seedbed covered with residues. This inherently complicates the sowing operation, although the exact implications depend on the used sowing implement and traction source. Some manual and animal-drawn implements may not require adaptation, but sowing does generally become more difficult and more time consuming.

In arable systems, two mechanised sowing options are potentially compatible with CRM. The first option uses a direct seed drill to establish the crop through the mulch. Such drills are specially designed for CRM and can be used on un-tilled (but arable) soil. The second option uses a conventional seed drill and implies the need to maintain at least some form of tillage. This option may thereby still incorporate a substantial portion of the residues (e.g. two passes with a disk harrow may incorporate half the residue present—CTIC, 2001). This can be an issue, especially in areas where mulch availability is already limited. Further, even low residue levels may still hamper the functioning of the seed drill. CRM may also require higher seed rates to ensure an adequate crop stand (Rice, 1983; Figueroa and Morales, 1992).

5.2.2. Weed management

CRM typically requires adaptations to weed management. First, as CRM affects the incidence of weeds. Mulches are known to control weed growth, typically by smothering them and/or through allelopathic effects (Akobundu, 1987). Second, as CRM affects weed management options. CRM curtails the intensity of soil tillage and use of pre-plant burning. It thereby foregoes the corresponding weed control effect these measures would have achieved. CRM typically relies on herbicides to substitute for such physical measures. The corresponding factor implications depend on actual production technology, the new herbicide technology and site-specific factors. CRM itself also affects herbicide use efficiency—for instance, due the presence of the mulch (Akobundu, 1987).

The reliance on herbicides for weed control makes their effective use imperative (Sandretto and Bull, 1996). However, herbicide use is knowledge intensive: it requires adequate knowledge of basic properties of products and application requirements. The choice of main crop, intercrop and/or subsequent crop may limit the choice of herbicides (e.g. preclude the use of residual herbicides like atrazine and 2,4-D—Tasistro, 1989). The knowledge intensity also implies that human skills are likely to have a profound influence on herbicide use efficiency.

Finally, some of CRM's weed management effects are interrelated and have an intertemporal dimension. The implied changes in weed management feed back into weed incidence: increased reliance on herbicides can induce changes in weed patterns (Rijn, 1982; Akobundu, 1987). Also, CRM conceivably allows for a more timely and effective weed management and can thereby gradually deplete the weed seed bank.

5.2.3. *Pest and disease management*

Many of the weed management considerations also apply to pest and disease management. Incorporation and burning of crop residues frequently are used as phytosanitary measures, whereas CRM curtails their use. The effect of CRM on pests and diseases is varied (Akobundu, 1987; Ortega, 1989; Unger, 1990). By retaining the crop residues, CRM may enhance the carry-over of both pest and disease organisms and their natural enemies (Rijn, 1982; Thurston, 1992). The presence of the mulch may reduce the transmittal of plant diseases by rain-splash (Thurston, 1992). CRM thus simultaneously affects the incidence and management of pests and diseases.

5.2.4. *Nutrient management*

CRM affects nutrient management by altering nutrient availability and fertiliser use efficiency. The retention of the crop residues as mulch affects the release, immobilisation and loss of nutrients. Leguminous crop residues typically have a low C:N-ratio and tend to ameliorate N-availability. Alternatively, cereal crop residues typically have a high C:N-ratio and may actually exacerbate N-stress by temporary N-immobilisation. This implies a lower N-availability for the crop until a new equilibrium is established (Barreto, 1989). On the other hand, phosphorous (P) is more effectively available under CRM (Moldenhauer et al., 1994). The initial years may thus require an investment into the revolving fund of nutrients in the form of a higher N dosage—though the reverse may be true in later years (Rijn, 1982; Shenk et al., 1983; Barreto, 1989; Moldenhauer et al., 1994). In addition, there tends to be an interaction between CRM and application rates during the initial years (Fig. 4). At low nitrogen application levels, conventional (no mulch) systems typically outyield CRM. However, as N rates are increased, the response curves intersect and CRM starts to outyield (Logan et al., 1991). A crossover point (X* in Fig. 4) of around 80–100 kg N ha^{-1} has been reported for maize in the USA and Central America (Phillips et al., 1980; Zea and Bolaños, 1997). N efficiency also varies over N source, as ammonia volatilisation can be substantial when applied superficially. Splitting N application may increase efficiency (Barreto, 1989). Fertiliser efficiency considerations are further compounded by the interaction with the water conservation effect of CRM. This reduces runoff losses and increases crop response due to higher plant available water.

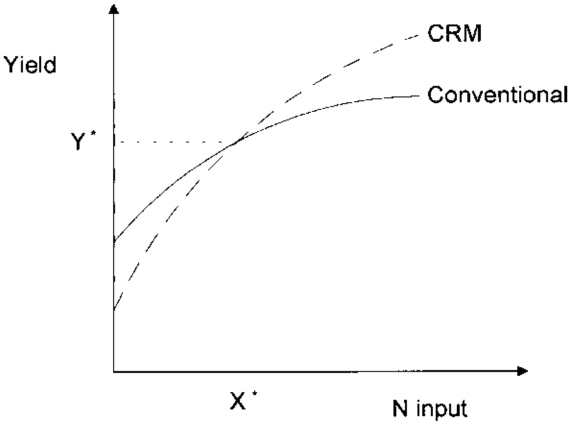

Fig. 4. Response of crop to N fertiliser with different production technology.

In sum, CRM is not a simple add-on technology—but affects both crop growth and crop management (Fig. 5). For most farmers, its adoption would imply major changes in crop management—both in terms of necessary and complementary cultural practices. CRM, therefore, is not an easily transferable single component technology. Instead, it is a complete package of cultural practices (Pierce, 1985; Lal, 1989; Lal et al., 1990). Such a package is not likely to fit in seamlessly into the widely varying production systems in developing countries. The appropriateness of CRM thus depends on both biophysical and socio-economic factors and their interactions (Lal, 1985, 1989, 1991).

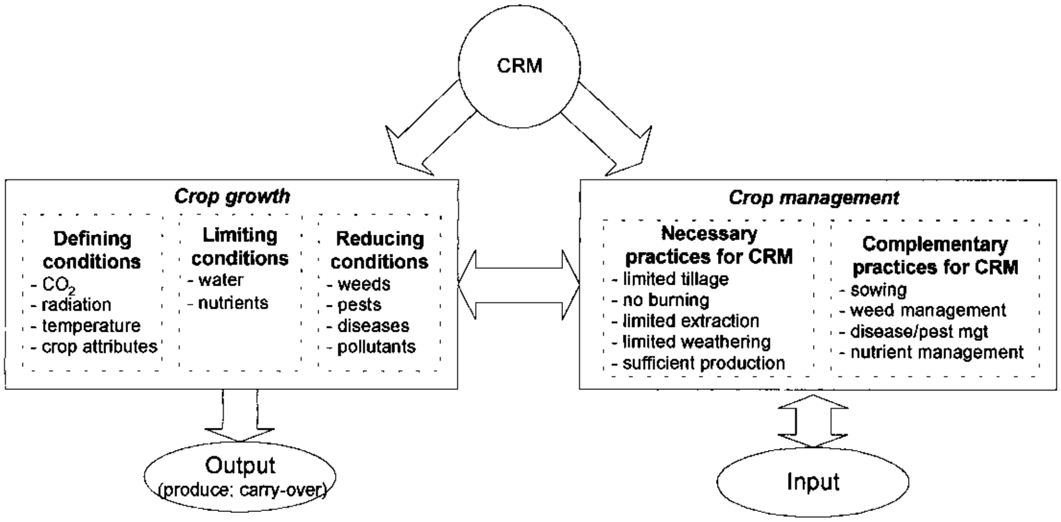

Fig. 5. Crop system implications to CRM.

Therefore, the CRM knowledge base developed in the USA, Canada and Australia is not directly transferable to developing countries. Instead, one would expect the need for substantial adaptive research (Thomas et al., 1983).

6. Socio-economic implications of CRM

CRM implies many changes for crop management, and in turn these changes have wider implications for the farm household system and society at large. To assess the actual potential of the CRM technology, a comprehensive assessment of the socio-economic implications is required (Erenstein, 1999b). This implies two levels of socio-economic analysis: the private and social viewpoint.

6.1. Private assessment

CRM implies a basket of management practices with numerous implications for crop management. In turn, these changes may have repercussions or provide opportunities at the farm level. The paramount private question is whether the aggregate benefits and costs of applying CRM are in the interest of the farm household. The private assessment of the CRM-induced changes thereby conveys the underlying trade-offs for the farm household. In the end, the farm household's decision to adopt hinges on whether CRM enhances the household's (expected) utility, which is more likely when adoption implies substantial private returns.

Private returns are a function of the magnitude and value of all the underlying biophysical changes at the crop and farm level (see Erenstein, 1999b for a conceptual framework). The foregoing has highlighted that the number of changes can be substantial—whereas their actual magnitude and value are likely to be household specific. Consequently, the private returns to adopting CRM are likely to vary over farm households. An important valuation aspect relates to the timing of the changes. Farmers in developing countries typically have a pronounced time preference—whereby immediate costs and benefits receive a substantially higher value than those incurred in the future.

In general, opportunity benefits are likely to be substantial whenever CRM's factor substitution frees scarce resources. Opportunity and relative costs of the factors involved are therefore important. In manual agricultural systems, traditional land preparation and weeding are very labour intensive. By substituting herbicides for such laborious measures, CRM can imply substantial labour savings. However, the actual potential of such change is to a large extent determined by the relative costs of labour and herbicide use. In mechanised systems, CRM tends to substitute herbicides for tillage and adapt the sowing operation. Such changes implied substantial labour and capital savings in the USA (Rice, 1983; Crosson, 1985; Harman and Wiese, 1985; Unger, 1990; Moldenhauer et al., 1994; Sandretto and Bull, 1996).

Factor substitution can alleviate crop management bottlenecks—particularly during land preparation and/or weeding. In land abundant situations this can ostensibly allow for an increase in the area that can be adequately cropped. Alternatively, it may enhance the timeliness of crop management and thereby favourably affect productivity. CRM potentially also offers more flexibility in terms of crop establishment (e.g. less time needed for land preparation; enhanced workability in mechanised systems). This typically reduces the turnaround time between crops. Occasionally, this may allow for an increase in land-use intensity by enabling the cultivation of a second crop (further aided by the enhanced availability of residual moisture under CRM).

Alternatively, opportunity costs are likely to be high whenever CRM's resource demands compete directly with the farm household's other established productive or consumptive activities. For a positive return in such instances, CRM needs to outperform the competing activities' contributions to the objective set. Further, established activities reflect the farm household's adaptation to the internal and external conditioning variables. Some of these conditioning variables are also likely to constrain CRM, and thereby tend to raise the underlying costs of adoption.

Scale implications are also likely to influence private returns. CRM may entail substantial learning costs (Logan et al., 1991; Napier et al., 1991; Harrington, 1994)—especially in developing countries. It also may entail lumpy investments in implements and residue protection measures (firebreaks; fencing), with corresponding economies of scale. These create differential start-up costs by size of farm and crop system.

Private economic returns ensured that the promotion of CRM practices was not ignored in the USA. Indeed, CRM's cost-reducing potential in the short-term in the USA is regularly flagged as the determinant of its success there (Buttel and Swanson, 1986; Miranowski, 1986; Gajewski et al., 1992). CRM proved to be economically attractive even without considering long-term productivity effects and spatial externalities (Fletcher and Seitz, 1986). The conservation benefits apparently were of secondary interest (Allmaras and Dowdy, 1985; Allmaras et al., 1991). In fact, much of the CRM area in the USA is actually located on land that is not particularly erodible (Crosson, 1985).

The complexity of the CRM technology and the farmers' interest in private returns also presents a dilemma. From a conservation point of view, the critical component of CRM is the presence of crop residues as mulch. From a farmer's point of view, the productivity effects are of particular interest—and these are only partially related to the mulch component. The conservation and crop yield effects are largely embodied in the same mulch component. However, the other factor productivity effects are not—being dependant on the factor saving potential of some of the underlying management changes. Consequently, there is a real danger of disarticulating the conservation and productivity aspects. Indeed, some of the more attractive changes may therefore be implemented as such, without actually ensuring retention of sufficient residues as mulch. For instance, farmers may adopt herbicides and/or reduced tillage practices for being economically attractive in their own right. However, by themselves such changes may be a necessary, but not sufficient condition for CRM adoption.

6.2. Social assessment

The socio-economic implications of CRM are not limited to the individual farm household but also affect society at large. Therefore, a social assessment is needed to assess whether the aggregate social benefits and costs of applying CRM are in the interest of society. CRM offers the potential to redress a number of the negative externalities traditionally associated with agriculture. One may therefore expect that CRM has a unequivocally positive social and environmental impact. However, the complexity of the technology and co-existence of several market imperfections implies that alleviating one may actually exacerbate another. Another controversial issue is the frequent dependence of CRM on herbicides—and the new problems this may impose. However, herbicide use is not limited to CRM. For instance, in the USA there seems to be a heavy dependence on herbicides regardless of tillage and residue management (Lal, 1989). The social and environmental impact of CRM therefore depends on the net aggregate effect of the underlying trade-offs.

The off-site effects of CRM are however not straightforward. On the one hand, CRM may reduce risks of surface water pollution by reducing both soil erosion and runoff. On the other, it may increase those risks through its reliance on herbicides and the surface application of agrochemicals (Lal, 1991). Fawcett et al. (1994) highlight that, on average, CRM actually reduced herbicide runoff in the USA. However, herbicide runoff may be equal or increased in case of heavy rainfall soon after application; or when infiltration is limited (ibid). Herbicide runoff also depends on soil adsorption. The soil tightly adsorbs some herbicides (e.g. paraquat and glyphosate). Such herbicides do not form a significant threat to surface water as long as soil erosion is seriously controlled—as in the case of CRM. However, most herbicides are not tightly adsorbed by the soil, and are therefore liable to runoff loss (Fawcett et al., 1994).

CRM and the resultant higher water infiltration may increase risks of leaching biocides and fertiliser (e.g. nitrates)—and thus of polluting groundwater. However, the evidence for this is not conclusive and the processes complex. In any case, biocide concentrations tend to be substantially higher in surface water than in shallow groundwater (Papendick et al., 1991; Fawcett et al., 1994). In developing countries, even less is known about the retention, biodegradation and movement of agrochemicals in surface and subsurface waters (Lal, 1989). This is especially problematic as rural people in developing regions often use surface water directly (Akobundu, 1987; Anderson and Thampapillai, 1990).By foregoing the use of fire, CRM also greatly reduces the risk of wildfires and the subsequent damages these impose on ecosystems and property (Ravnborg et al., 1996). For example, in the Mexican State of Chiapas, burning of residues was identified as the major cause of forest fires (Sandoval, 1994). In fact, protecting forest resources was part of the rationale for a recent law that severely restricts burning as a land preparation measure in the state. As farmers forego the use of fire the emission of particulates is also drastically reduced. Times of widespread pre-plant burning traditionally give rise to severe air pollution problems.

The reliance of CRM on herbicides may also impose human health costs for the user. Most modern herbicides are organic compounds relatively non-toxic to man and animals—belonging to class III and IV of the toxicity rating scale (Akobundu, 1987). Still, no herbicide is entirely safe and health costs depend on product type and duration and level of exposure However, factual evidence of herbicide-related health costs in developing countries is typically incomplete. Still, the hazards of herbicide use tend to be substantial in developing countries due to (i) the type of chemicals used (e.g. paraquat); (ii) limited human capital; (iii) lax safety measures; and (iv) the mode of application (Erenstein, 1999b). With the advent of herbicide use world-wide—and in the USA in particular—new chemicals that better meet the needs of the farmer and the environment are increasingly being developed and marketed (Laflen and Onstad, 1994). Therefore, the prospects for CRM's net social and environmental effect are likely to improve.

CRM therefore brings into play a number of environmental implications that not only transcend the farm boundary, but also transcend the traditional externalities associated with soil conservation. However, the net environmental and health impact remains fuzzy and controversial, particularly in developing countries. Valuing such impact in economic terms to assess the social implications is even more problematic. Indeed, such valuation is subject to a number of methodological difficulties (Erenstein, 1999b) and will be highly site-specific.

7. Conclusion

The paper evaluated some basic technological issues of CRM in (semi-)tropical countries and a number of conclusions can be drawn. First, the definition of conservation tillage and related practices is controversial and confusing. CRM is therefore proposed as the most adequate term for the technology. CRM is defined as a technology whereby at the time of crop emergence at least 30% of the soil surface is covered by organic residue of the previous crop.

A second conclusion is that CRM is a complex technology. Part of the complexity arises from CRM being a dual-purpose technology that combines conservation and productivity effects. Further adding to the complexity, CRM is not a single component technology but a basket of necessary and complementary management practices.

A third conclusion is that the potential of CRM is site-specific—i.e. CRM is no technological panacea. The actual implications of CRM depend on the local biophysical and socio-economic environment—and thereby differ substantially between developed and developing country agricultural settings. To assess the actual potential a comprehensive socio-economic assessment is needed. An assessment from the private viewpoint will highlight the likely farmer acceptance of the technology. An assessment from the social viewpoint will highlight whether supportive or corrective policy intervention is justified.

The socio-economic assessment is however confounded by a number of issues. In part this is a direct result of the aforementioned complexity. For instance, CRM gives rise to new externalities—both positive and negative—that make its net environmental impact fuzzy and controversial. Another confounding factor is the 30% soil-cover threshold in the CRM definition. This threshold is ambiguous—particularly in view of the asymptotic decline of relative erosion with increasing cover—and problematic to assess reliably at limited cost.

Although CRM can be viewed as a dual-purpose technology, farmers are likely to emphasise the productivity aspects of CRM, with conservation as added benefit. Emphasis on the productivity aspects can help explain incomplete, partial adoption of CRM practices. Indeed, a number of crop management practices are a necessary, but not sufficient condition for CRM adoption.

In the end, CRM can be best viewed as a technological option within a basket of conservation farming technologies. Technological development should thereby not limit itself to CRM. Other technological options are also needed so as to provide developing country farmers with a basket of potentially suitable technological choices. Within the diverse agricultural settings in (semi-)tropical countries, CRM has most potential whenever its use is economically attractive from the private viewpoint. Therefore, there is a need to target the development of CRM to those instances where it would conceivably generate immediate economic returns for the farm household, with longer term resource conservation and reduced negative externalities as added benefits.

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