Review

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The increasing importance of herbicides in worldwide crop production

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Abstract

Herbicide use is increasingly being adopted around the world. Many developing countries (India, China, Bangladesh) are facing shortages of workers to hand weed fields as millions of people move from rural to urban areas. In these countries, herbicides are far cheaper and more readily available than labor for hand weeding. History shows that in industrializing countries in the past, including the United States, Germany, Japan and South Korea, the same phenomenon has occurred – as workers have left agriculture, herbicides have been adopted. It is inevitable that herbicide use will increase in sub-Saharan Africa, not only because millions of people are leaving rural areas, creating shortages of hand weeders, but also because of the need to increase crop yields. Hand weeding has never been a very efficient method of weed control – often performed too late and not frequently enough. Uncontrolled weeds have been a major cause of low crop yields in sub-Saharan Africa for a long time. In many parts of the world, herbicides are being increasingly used to replace tillage in order to improve environmental conditions. In comparison with tillage, herbicide use reduces erosion, fuel use, greenhouse gas emissions and nutrient run-off and conserves water.

Keywords: herbicides; weeds; yields; labor; maize; wheat; rice

1 INTRODUCTION

The use of herbicides is increasing in worldwide crop production. The value of the worldwide herbicide market grew by 39% between 2002 and 2011 and is projected to grow by another 11% by 2016.[1] Herbicides are being rapidly adopted in developing countries that face shortages of hand weeding labor and the need to raise crop yields.[2] Improved weed control with herbicides has the potential greatly to improve crop yields in many developing countries in the near future.[3] Increased herbicide use promotes fertilizer use, which leads to even greater yield increases.[4]

Research has shown that, if enough hand weeding is done at the optimal times, crop yields are not reduced by weed competition.[5] In reality, crop fields are seldom adequately weeded by hand; weeding is tedious and time consuming. Laborers are not always available when needed.[6] Weeding is often done late, causing drastic losses in yield.[7] The use of herbicides has gained impetus from the general rise in farm wages as a consequence of overall economic growth and growth in non-farm employment opportunities, particularly in Asia.[8] Adequate non-chemical controls for weeds are not available, and herbicide use is increasing dramatically as a result of rising opportunity costs of labor across the developing world.[8]

Herbicide use is increasing in many countries where tillage and flooding for weed control are being reduced in order to conserve natural resources: soil, water and energy. Reduced tillage dramatically reduces direct fuel consumption relative to conventional tillage with the moldboard plow. Not only does one herbicide application substitute for several tillage trips, tillage equipment is also heavier than herbicide sprayers and needs more energy to pull steel implements through the soil. A moldboard plow consumes 17 times more diesel fuel per unit area than a herbicide sprayer. A row-crop cultivator requires 4 times more fuel per trip across a field than a herbicide sprayer.[9]

Agricultural greenhouse gas (GHG) emissions can be curbed by decreasing fuel use by field equipment. Each gallon of diesel fuel burned by a tractor is estimated to release 10 180 g of CO_2.[10] The largest contribution to reducing the CO_2 emissions associated with farming activities is made by the reduction in tillage operations.[11]

2 DEVELOPED COUNTRIES

Herbicides were rapidly adopted in western European countries, the United States, Canada, South Korea and Japan in the 1950s–1970s. As these countries rapidly industrialized, millions of farmworkers left rural areas, which created shortages of workers for hand weeding and tillage operations.

In Germany, industry needed an increasing number of employees around 1960, and rural people left their fields. Without herbicides to replace the departing workers, it is not likely that widespread crop production would have been practiced any longer in Germany.[12]

In Japan, herbicide adoption reduced the amount of time required for weeding operations by 97%.[13] In Japan, perfect hand weeding of the nation's rice fields would require the work of 1.89 million people every day for 60 days, which is totally impractical today.[14]

Prior to the 1960s, the Korean economy was one of the poorest in the world. In the 1960s the Korean government embarked on a policy of industrialization, and the economy began to take off. Rising living standards and employment opportunities in urban areas drew farmers away from urban areas. More than 12 million

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people migrated from rural to urban areas in the period from 1957 to 1982. In Korea, manual weeding had been the prevalent control for centuries. As labor shortages appeared, herbicide use was recommended, and by 1971, 27% of the rice hectares were treated.[15] By 1977, 65% of the total rice area was treated with herbicides, and since the 1980s, 100% of Korea's rice hectares have been treated with herbicides.[16]

Herbicides greatly improved weed control, and their use contributed significantly to increased crop yields. In the United States, increased herbicide use accounted for 20% of the increase in corn yields and 62% of the increase in soybean yields from 1964 to 1979.[17,18]

Herbicides have been identified as the main factor underlying the increased wheat yield in Canada since the 1960s.[19] This control resulted not only in reduced competition from weeds but also in better seedbed moisture because fewer cultivations were needed. Because of the ability to control weeds with chemicals, it was possible to seed shallowly into a moist seedbed immediately after one cultivation, as numerous spring cultivations with a resultant loss of soil moisture were no longer necessary.[19]

Crop production on the Canadian prairies is limited mainly by lack of water. Taking land out of crop production for a year (fallowing) to conserve water has been practiced for many years. The 1970s marked the introduction of glyphosate; this herbicide transformed grain production in western Canada as it facilitated the widespread adoption of minimum-till and zero-till farming systems.[20] These systems have reduced fuel and labor costs and have significantly increased soil and water conservation in the semi-arid prairies. Each tillage pass that is eliminated saves an estimated 5.9 L ha^{-1} of diesel. The increased cost of diesel fuel and reduced price of glyphosate in Canada in the 1980s–1990s spurred the adoption of no-till. Direct seeding (conservation tillage) practices are now the norm; 70–80% of the land is direct seeded in western Canada. Greater moisture conservation has facilitated a 70% reduction in fallow.[21] Herbicides have made these changes possible.

Australian grain growers have been reducing their use of cultivation since the 1970s, with 44% of the nation's crop in no-till by 2001.[22] The falling price of the predominant knockdown herbicide, glyphosate, had a significantly positive effect on the adoption of no-till, with 78% of farmers practicing no-till in 2008.[23] The use of no-till means that the seed is sown with minimum soil disturbance, reducing evaporation and increasing yields. In addition, no-till systems allow for earlier planting.[24] Research demonstrated that using herbicides instead of tillage resulted in 27 mm of extra water in the soil profile and an increase in grain yields of 15–25%.[25]

In a wheat-fallow system in semi-arid subtropical Queensland, Australia, practicing zero tillage reduced fossil fuel emissions from machinery operation by 2.2 million g CO_2 ha^{-1} over 33 years, or by 67 kg CO_2 ha^{-1} $year^{-1}$ (4–5 tillage operations with a chisel plow to 10 cm during fallow each year were replaced by one herbicide spray).[11]

All Scandinavian countries are signatories to the North Sea Treaty of 1987 which includes a goal of reducing nutrient inputs into the North Sea by half. Research has shown that a considerable amount of phosphorus moves into waterways with eroded soil from fields that have been plowed in the autumn. In Norway and Finland, subsidies have been provided for switching from fall plowing to summer plowing or direct seeding with no plowing. Half of Norway's cereal acres are no longer plowed in the autumn. The reduction in erosion from switching from fall plowing is estimated to be 85%.[26] Norway has determined that an absolute prerequisite for the success of these alternative tillage systems is that perennial weeds, as well as some winter-hardy annuals, are removed by spraying herbicides.[27] In Finland, in the 1990s, plowing was still the standard practice in spring cereal fields, while the latest statistics show that only half of the cereal field area is currently plowed.[28] At the same time, the sales of glyphosate have more than doubled within a decade in Finland.[28]

3 ASIA

Asian crop fields have been incurring yield losses due to inadequate weeding. A 1991–1995 survey of rice fields in tropical Asia determined that uncontrolled weeds in farmers' fields were the most significant pest factor in reducing yields: rice yields were being reduced by 23% from weeds growing above the rice canopy and by 21% from weeds growing below the rice canopy (not additive, considered individually).[29]

As more Asian economies have been industrializing, millions of people are migrating from rural to urban areas, creating shortages of workers for hand weeding and increasing the cost of hand weeding when labor is available.[30] Wage rates for farm workers in southeast Asia have steadily increased; the average wage rate today is 5 times greater than in the 1970s.[6] Increases of between 100 and 200% in the current labor price are realistic expectations within 5–10 years.[30] Farmers are left with little choice but to reduce labor and production costs, particularly for the most labor-intensive tasks, such as weeding.[31]

In the Philippines, the proportion of rice farmers using herbicides increased from 14% in 1966 to 61% in 1974.[6] Today, 96–98% of Philippine rice farmers use herbicides.[32] A recent study determined that, with increased labor cost, herbicide application in rice fields is superior to manual weeding even at the lowest weed density by \$US 25–54 ha^{-1}.[30] At the highest weed density and highest labor cost, herbicide application is approximately 80% (about \$US 200 ha^{-1}) more profitable than hand weeding.[30]

In Bangladesh, the loss in rice yield in farmers' fields as a result of poor weed control has been determined to be 43–51%.[7] The yield gap between herbicide use and hand weeding is as high as 1 mt ha^{-1}, with 30% of farmers losing in excess of 500 kg ha^{-1} in the absence of herbicides.[33] In Bangladesh, pre-emergence herbicides in rice are 38–46% cheaper than one hand weeding.[34] Economic analysis of rice production in Bangladesh revealed that net income from herbicide application was 116% higher than hand weeding owing to increased yield and lower cost.[7]

With the introduction of higher-yielding varieties of wheat responsive to intensive irrigation and fertilizer application, wheat production in India and Pakistan increased dramatically. However, there is a wide gap between potential yield of wheat and yield obtained in farmers' fields.[35] Weed infestation is the main cause of low wheat yields in Pakistan and India and is reported to reduce wheat production by 25–30%.[36,37] Traditionally, weeds were controlled in wheat with two hand weedings at an interval of 2 weeks. However, hand weeding schedules have become impossible owing to the high cost and scarcity of labor.[38] Hence, the use of herbicides in wheat is the only acceptable way for effective weed management in wheat.[39] One of the prime reasons for recent increased wheat yields in Pakistan was the introduction of very effective grass-specific herbicides, which were feasible owing to the increased support price for wheat.[40] Recent studies showed that herbicide treatment gave 87–90% weed control, with a consequent 19–21% increase in grain yield.[40]

To hand weed India's crop fields adequately, approximately 9 billion person-days of labor would be required.[41] In reality, hand weeding in India has been inadequate and crop losses have resulted. In one regional survey, between 15 and 30% of the fields of all major crops were never hand weeded.[42] A little less than half the fields were hand weeded once. More than 40% of the fields were hand weeded for the first time after the critical first 36 days after sowing.[42] Recent government mandates such as the National Rural Employment Guarantee Act has created labor shortages for weeding in India because guaranteed employment and wages mandated by the Act have outpaced regular pay, making hand weeding an unsustainable practice.[43] Thus, in recent years a shortage of labor has been occurring on rural farms.[44] Until recently in India, herbicides were used on 10% of the wheat hectares to control grass weed species and on 20–25% of the hectares to control broadleaf species.[45] Since 2005, the value of the herbicide market in India has doubled.[1] The Indian market for herbicides is expected to grow about 40% annually over the next 5 years.[46]

In the past in China, farmers weeded by hand. About 1 billion person-days of labor would be required to hand weed China's rice fields adequately.[47] However, since the late 1970s, rapid expansion of industries has caused an outflow of the farming population as well as a corresponding increase in wages, making herbicide use more attractive to farmers.[2] From 1978 to 1990, with encouragement and promotion from the research and extension sectors, an increasing number of Chinese farmers began to adopt herbicides to control weeds.[48] The herbicide application areas of crop fields have steadily increased from less than 1 million ha in the early 1970s to more than 70 million ha in 2005.[2]

In 1973 in China, it was estimated that rice crop losses due to weeds were 40%, even though the crop was hand weeded several times. In 1988, with increased adoption of herbicides, the loss of rice to weeds was estimated to be 6–8%.[47] A 2010 survey of a rice production zone of the Yunnan plateau indicated that current yield losses of rice to uncontrolled weeds above the canopy was 2.8%, while below the canopy uncontrolled weeds resulted in a 1.5% yield loss (considered separately).[49] The researchers noted that the weed loss estimates were considerably lower than earlier estimates and cited the adoption of herbicides as a cause.[49]

Traditionally, manual hand weeding has been the predominant method of weed control used by maize farmers in Asia.[50] If performed with enough frequency and at the right times, hand weeding results in maize yields that are equivalent to yields with herbicides.[5] However, because of the shortage of labor and frequent monsoon rains during the early growth period of maize, hand weeding is often delayed or neglected altogether.[5] As a result, severe uncontrolled weed infestations have been identified as one of the major reasons for low maize yields in Asia.[51] In the Philippines, actual losses due to weeds in maize fields have been reported at 15–30%.[52] In India, 39 trials compared maize yields with herbicides to yields obtained with weed control methods; the maize yields with herbicides were 19% higher.[3]

In China, the inability to weed on time has been identified as a major reason for the loss in maize yields in nine out of 12 villages.[53] In India, research demonstrated that herbicide treatments in maize produced 83% more yield in comparison with the practice of plowing the fields to remove weeds.[54] In Pakistan, maize yield losses due to weeds has been estimated at 14%.[55] In India, weeds are ranked as the worst production constraint by maize farmers, and herbicides are not used.[56]

In South Asia, rice has been traditionally grown by manually transplanting seedlings into flooded soil. Flooding benefits rice by controlling the first flush of weeds and provides the rice seedlings with a head start on subsequent weed flushes.[57] Weeds that emerge during the season have been typically controlled by hand weeding. Water scarcity threatens the sustainability of rice production in Asia. Rice consumes about 50% of total irrigation water used. Agriculture's share of water is declining owing to competition with domestic household and industrial use. In Asia, the share of water used for agriculture declined from 98 to 80% in the last century, and is likely to drop to 72% by 2020.[57] Rice can be planted by sowing seeds in dry soil instead of transplanting rice seedlings into flooded soils. The dry planting method requires 35–57% less water than transplanting seedlings into flooded fields.[58,59] However, weeds are more problematic in the dry system because they are not controlled by flooding. A variety of herbicides have been screened and found to be effective for burndown, pre-emergence and post-emergence control in dry-seeded systems. Virtually all rice farmers who practice direct seeding adopt herbicides.[59,60]

The data from a survey of farmers adopting zero tillage in Haryana (India) and Punjab (Pakistan) indicated an average saving of 35 L ha^{-1} of diesel for land preparation, or 98 kg C ha^{-1}. Farmers averaged one pass of the tractor with zero tillage for seeding versus eight passes for tilled soils.[61]

4 CIS COUNTRIES/EASTERN EUROPE

In Russia in the 1960s, research demonstrated that herbicide use led to a 50% increase in cereal yield on state farms.[62] Herbicide use in Russia rose from 25 million ha in 1968 to 47 million ha in 1973.[63] The dissolution of the Soviet Union in 1991 led to privatization of the collective farms. Government support of agriculture collapsed and many farms were without the financial resources to buy herbicides. The reduced use of herbicides was a major factor resulting in lower wheat production in Russia in the 1990s. The annual loss of Russian cereal production as a result of weed infestation in 1996–2000 was estimated to be 10.5 million t.[64] Losses in the 1990s would have been greater had farmers been unable to use herbicides altogether. Estimates by the Russian Academy of Agricultural Sciences for 1990–1999 were that the additional yield on the 15 million ha treated with herbicides was 6 million t $year^{-1}$.[65] Measures aimed at suppressing weeds were identified as the foremost priority for improving cereal production in Russia.[64] In recent years, the Russian government has introduced policies to increase the availability and use of herbicides in crop production. The herbicide market in Russia in 2010 was valued 2.8 times higher than in 2003.[1]

In the Ukraine in the early 2000s, increasing weed infestation in crops was identified as one of the main problems causing severe yield losses.[66] In 2002, only about 50% of the maize area in the Ukraine was treated with herbicides; by 2012, the herbicide-treated maize area in the Ukraine had risen to 90%.[67]

In Kazakhstan, approximately 2.5 million ha of grain are heavily infested with weeds.[68] Government subsidies for herbicide purchase of $US 2–3 million $year^{-1}$ resulted in herbicide use on 1.4 million ha. Weed infestation has decreased by about 15% every year since the weed-control campaign was launched.[68]

In 2003, Poland voted to join the European Union (EU). During Poland's preparation for EU membership, Polish agriculture benefited from EU funds allocated under preaccession policies. These funds from the EU were aimed at bringing agricultural practices in Poland in line with those of other EU countries. As a result, Polish farmers had more funds to buy herbicides. Sales of

herbicides in Poland in terms of volume were 3 times higher in 2008 than in 2003.[69]

5 SUB-SAHARAN AFRICA

Hand weeding is the predominant weed control practice of smallholder maize farmers in Africa. Although a lot of energy is expended in removing weeds by hand, African crop yields are generally very low owing to weed competition, as a result of untimely and ineffective weed control. Late weeding results in crop losses, especially if it is carried out after the critical period of weed competition. In many instances, labor constraints force farmers to plant their crops after weeds have begun to grow. Such crops are easily smothered by weeds, and fields are abandoned. In Africa, yield losses in farmers' fields range from 25% to total crop failure because farmers are unable to perform the necessary weedings at the optimal time. A recent report from Africa estimates that 2.3 million t of rice is lost annually as a result of weed infestations (15% of the total potential production).[70]

Average yields obtained by smallholder farms are considerably less than yields in African research plots utilizing best management practices. Smallholder maize yields are typically 1–2 t ha^{-1} in comparison with 8 t ha^{-1} achieved in research plots. The failure of farmers to replicate the weed control practices of the research farms is a major cause of low maize yields. At the experimental farms it has been determined that maximum yields are achieved if maize fields are kept weed free for the first 56 days after planting.[71] One week's delay in first weeding may reduce maize yields by one-third.[72] On most farms, weeding usually competes with other farm activities and is postponed to a later date. In Malawi, nationwide survey data suggest that one-third of the area planted to maize by smallholders is either left unweeded or weeded after the critical first 6 weeks.[72] Maize is generally the first crop planted, and weeding becomes necessary at a time when labor is critical for planting cash crops such as groundnuts. Shortages of labor early in the season results in delayed weeding and subsequent maize yield losses of 15–90% due to weed competition.[73] In Nigeria, maize farmers' weeding practice (one weeding) resulted in a 42% yield loss in comparison with fields weeded 3 times.[74]

The spraying of herbicides to remove weeds from maize fields is an alternative to hand weeding African fields. Experiments with herbicides to control weeds in maize crops have been conducted in sub-Saharan Africa since the 1960s. Smallholder farmers in Africa generally do not use herbicides, and adoption rates are less than 5%.[75,76] Although herbicides have been extensively studied in Africa, there was no mechanism to disseminate the technology to smallholders once the research process was over.

Maize yields doubled in Nigeria when atrazine was used.[77] In Zimbabwe, research with herbicides resulted in yield increases of up to 50% in maize.[78] Use of herbicides in Kenyan weed trials resulted in 33% higher maize yields than with the farmer practice of hand weeding on account of better weed control.[79]

The adoption of herbicides in African maize fields is likely to lead to increased production not only as a result of improved weed control but also by facilitating the adoption of fertilizer use and expansion of planted acres. In spite of being promoted for 40 years, fertilizer use in sub-Saharan Africa remains low, with only 5% of smallholders adopting their use.[80] The benefits of fertilizer depend on weed control. The application of fertilizers causes more weeds to grow, which in turn increases the need for more hand weeding. By controlling the weed problem with herbicides, maize farmers will be more likely to use fertilizers for even greater maize yield increase.[4] African farmers often plant only 50% of their available fields to crops, leaving the remaining area fallow, because they make a determination that not enough labor would be available to weed the additional fields.[81] By greatly reducing the amount of labor required for weeding, the adoption of herbicides can lead to a greater area planted to crops.

In recent years, with rapid urbanization occurring in many African countries, shortages of workers for hand weeding have increased. Research has shown that herbicides are about one-third the cost of hired labor for hand weeding.[82] Because of high labor costs, hand weeding is no longer considered sustainable for African agriculture, and organizations such as the International Institute for Tropical Agriculture (IITA) are recommending the use of herbicides.[83] In some African countries, such as Mali, herbicide use has doubled in the past 5 years.[84]

6 NORTH AFRICA

In water-deficient areas, such as North Africa, where the potential for increasing crop water supply is limited, small increases in available water can result in large relative increases in yield.[85] Theoretically, residual moisture from a fallow year should increase the available moisture and therefore crop yields in the subsequent cropped year. However, in practice in North Africa, fallows are kept 'weedy' and grazed. At the end of the fallow season there is little stored moisture and the soil is bare and prone to erosion. With tillage for removing weeds, any perceived advantage of fallow is eliminated.[85] Research has demonstrated that, where weeds are controlled by herbicides instead of conventional tillage, stored soil water is increased by 85 mm.[85]

7 LATIN AMERICA

A series of changes in government policies and economic conditions resulted in stagnation of crop production in Argentina in the 1980s (rising export taxes, frozen bank accounts, deep debt and the total collapse of credit). Argentine farmers minimized their use of inputs as a risk management strategy at a time of economic instability. Since the 1990s, the acreage and production of grain and oilseed crops (particularly soybeans and maize) have increased dramatically. The primary cause of the expansion of production and economic viability of soybean and maize production in Argentina was the widespread adoption of herbicides (particularly glyphosate) for weed control. The widespread adoption of glyphosate in Argentina was in large part due to the almost total adoption of glyphosate-resistant soybeans.[86] Rapid adoption of glyphosate-resistant soybeans occurred in Brazil, Uruguay and Paraguay.[87] The increased use of glyphosate facilitated the rapid adoption of no-till crop production, reversing decades of destructive farming practices and leading to higher crop yields, economic viability and expansion of planted acres.

In Argentina, tillage had been the traditional way of removing weeds from crop fields. However, tillage caused reductions in soil nutrients, soil organic matter, soil structure and soil moisture and increased soil erosion.[88] In the early 1990s, some Argentine researchers cited empirical and experimental evidence of the potential for no-till to reverse the negative effects of tillage.[89] At the same time, the possibility of increasing total production and supplying both the domestic and the international market was perceived by Argentinian farmers as an important opportunity.[90] Research demonstrated that an additional 4 inches of soil water was accumulated in the no-till system, which facilitated the expansion of soybean and maize acreage into areas where water

availability had limited plantings.[88] In many cases, no-till reduced erosion by 90% from 10 t ha^{-1} or more.[88] Soybean yield increased by 11%, while the cost of production decreased owing to savings in fuel and labor costs.[91] Effective, inexpensive herbicides made the no-till system viable in Argentina.

During the 1960s, a significant expansion of the area under soybean and winter wheat occurred in southern Brazil. The intensive plowing and disking and residue burning regimes widely adopted with these crops exposed bare soils to intensive rainfall, which in turn led to extensive soil erosion and associated economic losses throughout large tracts of southern Brazil.[92] The adoption of zero-till systems remained erratic throughout the 1970s owing mainly to the lack of suitable techniques to control weeds effectively and the lack of planters to work with the high volume of residues. The release of glyphosate in Brazil in the mid-1970s changed this situation by providing effective weed control without the need for tillage.[92] Farmers began to organize themselves into zero-tilling associations. Research has demonstrated that the productivity of crops has been consistently higher under no-till, with yields of maize, soybean and wheat cultivated under no-till being 17% higher than under conventional tillage.[93]

In Brazil, migration from rural to urban areas was fuelled by better wages in the cities, a consequence of the growing industrialization that was taking place. The rural population of Brazil decreased from 64% of the total population in 1950 to 32% in 1980 and 16% in 2010.[94] As a result, there were fewer workers in rural areas to do the work of weeding by hand or with tractors. A significant number of smallholder farmers in Brazil practice no-till. Surveys show that the reduced need for labor has been a major incentive for the adoption of no-till by smallholders.[93] The substitution of herbicides for hand weeding, plowing and harrowing reduced the need for labor in maize by 38%.[93]

In Brazil, it has been estimated that GHG emissions from machinery operations in no-till system areas are only 34% of the emissions in full-tillage systems.[95]

8 CONCLUSION

Weeds have to be controlled for successful crop production to occur. The centuries-old practice of hand weeding fields is no longer sustainable in the modern world. The human drudgery of hand weeding is one of the first tasks readily given up by workers as countries industrialize. The shortage of workers for hand weeding makes the use of herbicides inevitable throughout the world. Inefficient hand weeding (seldom enough, seldom at the right time) has meant significant yield losses to weeds throughout the world to this day. Significant crop losses due to weeds are simply not acceptable in a world where 2 billion more people will have to be fed in the next 40 years. Herbicide adoption will significantly increase crop yields and is key to greater adoption of fertilizer use, which will lead to even greater yields. Tillage for weed control has many drawbacks in comparison with herbicides – greater fuel use, greater erosion, greater greenhouse gas emissions and greater loss of water from soils. In a world facing climate change and severe water constraints, tillage has to be reduced. Herbicides are the key to sustainable crop production throughout the world and will remain the mainstay for weed control for the foreseeable future.

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