Agricultural adaptation to climate policies under technical change

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Keywords

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Abstract

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Numerous agricultural greenhouse gas emission mitigation options have been examined, experimented, and improved in the last two decades. Some argue that these options provide only a short term, low cost opportunity until a large set of emission friendly technologies are available in other sectors, particularly the energy sector (McCarl and Sands 2007). Others argue that consideration of non-greenhouse gas related environmental benefits suffices to make some mitigation strategies cost-effective even in absence of climate policies. For example, Lal (2004) document substantial co-benefits of carbon sequestration.

Agricultural mitigation options may be grouped into three distinct categories: a) emissions reductions, b) carbon sinks, and c) emission offsets (McCarl and Schneider, 2000). Within each category, there are numerous independent, competitive, or complementary options. This study analyzes yet another option, which affects all three categories: technical progress. Generally, technical progress in agriculture may result in a combination of cost savings for a given production level or production increases for a given input level. An important benefit of yield increasing management consists of reduced resource requirements, particular for land. Lower land requirements relax land prices and therefore lower cost of land-based mitigation options such as afforestation or energy crop plantations.

The search for more efficient agricultural greenhouse gas emission mitigation options usually focuses on boosting energy crop yields or carbon sequestration rates in soils and trees but ignores conventional crop yields unless it relates to carbon saving systems like reduced tillage. However, from an economic point there is no certainty that a 1 percent yield increase of say Miscanthus increases the agricultural greenhouse gas mitigation potential more than a 1 percent yield increase in conventionally tilled wheat. While the first option directly increases the emission offset potential per hectare, the second option decreases the opportunity cost across all land based mitigation options. Because the area shares of the affected crops might be very different, a small yield increase of a universally grown crop may be worth more than a large yield increase of a rare crop.

The objective of this study is to analyze how agricultural management adapts to climate policies and technical progress. Particularly, we want to examine whether the likely adaptation patterns change as crop production becomes more efficient. To do this we use the Agricultural Sector and Mitigation of Greenhouse Gas (ASMGHG) model and implement a general representation of technical change by assuming yield increases across certain crops without changes in production costs. One could, for example, interpret these general changes as the effects of genetic improvements. For the purpose of this study, a combined yield and cost adjustment would not yield additional insights because the effects of a low yield increase without cost change are similar to the effects of a higher yield improvement with increased costs.

Previous Studies

Numerous studies have examined the complex relations between agriculture, climate, and climate policies (Freibauer et al. 2004, Mall et al. 2006). Most studies focus on either climate change mitigation (Clemens and Ahlgrimm 2001, Smith and Almarez 2004) or climate change impacts. Few studies include both aspects (Olesen 2007). Agricultural climate impact studies address issues of yield and cost changes related to changes in CO_2 concentration, temperature, rainfall, and pest occurrence (Alexandrov et al. 2002, Tubiello et al. 2002). Climate mitigation studies generally comprise engineering (Wang and Dalal 2006, Cerri et al. 2007) or economic analyses (Pautsch et al. 2001, Antle et al. 2003, De Cara et al. 2005, Lubowski et al. 2006, Yoshimoto et al. 2007).

Engineering analyses exogenously prescribe management and technical changes and compute measures of technical potential (Cole et al. 1997, Phetteplace et al. 2001, Sartori et al. 2006, Smeets et al. 2007). These studies often contain a detailed representation of alternative technologies. Opportunity cost, market adjustments and their feedback on adaptation, however, are not accounted for and therefore estimated mitigation potentials are generally higher than those of economic analyses. The latter typically use much less technical detail on individual management options but portray competition and complementarities with other land uses and/or other potential mitigation options. The adaptation of land management often results from exogenous policy changes. Market adjustments are excluded in many regional economic studies which focus on the heterogeneity of farming conditions but - by assumption - use constant prices (for example Antle et al. 2003, De Cara et al. 2005, Lubowski et al. 2006). Analyses with endogenous prices (Schneider et al. 2007) come at the expense of a detailed account for spatial heterogeneity. This study uses this type of analysis and employs the ASMGHG model.

Previous ASMGHG applications have assessed economic emission mitigation potentials from land use and crop management changes. McCarl and Schneider (2001) show for relatively low carbon prices a domination of emission friendly crop management whereas higher prices attract more reductions through afforestation and bioenergy. Bioenergy options are investigated in more detail in Schneider and McCarl

(2003). Their study also shows how producer adaptations to climate policies change if the value of sink credits is discounted due to non-permanence. Adaptations also depend on the scope of climate policies, which may involve only a subset of all possible strategies. Schneider and McCarl (2005) illustrate how a policy directed only towards the energy sector will affect U.S. agriculture. Depending on the emission tax level and bioenergy refinery capacities, there will either be a switch to energy saving crop management or a combination of more intensive agriculture and bioenergy production. The impact of market feedbacks, adaptation choices, and other modeling assumptions has been studied by Schneider and McCarl (2006) and Schneider et al. (2007). Due to the large size of ASMGHG, all studies can only document a small selection of aggregated model output. This study will not only examine new aspects of agricultural greenhouse gas emission mitigation but also add insight to the interpretation of previous ASMGHG results.

The Agricultural Sector and Mitigation of Greenhouse Gas Model

The Agricultural Sector and Mitigation of Greenhouse Gas (ASMGHG) model represents US agriculture and trade relationships with foreign regions. The ASMGHG model is an expansion of the U.S. Agricultural Sector Model (ASM) (Chang et al. 1992, Chen 1999). It is a mathematical programming based, price-endogenous sector model of the agricultural sector, modified to include GHG emission accounting by Schneider (2000). ASMGHG also includes data on forestry production based on the FASOM model (Alig, Adams, and McCarl 1998). ASMGHG depicts production, consumption, and international trade in 63 U.S. regions for 22 traditional and 3 perennial energy crops, 29 animal products, 6 forest products and more than 60 processed agricultural products. Management choices include tillage, irrigation, fertilization, manure treatment, and animal feeding alternatives. Environmental accounts include levels of net GHG emission for CO2, CH4, and N2O; surface, subsurface, and groundwater pollution for nitrogen and phosphorous; and soil erosion.

ASMGHG simulates the market and trade equilibrium in agricultural markets of the United States and major foreign trading partners. Domestic and foreign supply and demand conditions are considered, as are regional production conditions and resource endowments. The market equilibrium reveals commodity and factor prices, levels of domestic production, export and import quantities, GHG emission management strategy adoption, resource usage, and environmental impacts.

Empirical Findings

This section describes the empirical findings of ASMGHG simulations with different assumptions about technological progress and climate policies. Technological progress is implemented as cost-free yield increase on a) all crops, b) annual food and fiber crops, or c) perennial energy crops. Furthermore, we assumed different levels of technological progress covering yield increases up to 50 percent. Climate policies are internalized via exogenous carbon equivalent prices on all greenhouse gas accounts in ASMGHG. Thus, while positive emissions are taxed, negative emissions are subsidized. To address the uncertainty of future climate policies, we use a price range between \$0 and \$500 per metric ton of carbon[1]. Combining the assumptions about yield increase,

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[1] Note that the market price for carbon in the first stage of the EU emission trading system has been below 1 Euro per ton. However, for the second trading period, running from 2008 to 2012, higher prices are expected because a) the permit volume will be lower and b) permits will be auctioned. High carbon values are included in this study to examine the impact of strong carbon policies and to gain insight in the model results. These benefits outweigh the small computational costs of running additional scenarios.

crop scope, and climate policy results in 750 scenarios, where each scenario corresponds to a separate ASMGHG solution.

The output of a single ASMGHG solution already contains millions of endogenous variables values and accordingly higher is the output of 750 solutions. To present the simulation results within the scope of a journal article, we focus on selected, aggregate measures. The use of aggregates has two additional advantages beyond brevity. First, as argued in Onal and McCarl (1991), sector models, while using sub-state level data, perform better on the aggregated national level. This holds in particular for ASMGHG which is calibrated on the national level. Second, aggregate measures contain and summarize many individual measures simultaneously. To answer the research questions of this study, we examine the combined impact of technological progress and climate policy in US agriculture on a) crop management adaptation, b) greenhouse gas emission mitigation, c) agricultural emission intensities, and d) agricultural market and economic surplus changes.

Crop management adaptation

Agricultural mitigation efforts may involve either relatively strong land use changes towards forests or perennial energy crop plantations or relatively light management changes on existing cropping systems. In ASMGHG, possible adaptations of existing crop management include alternative crop, tillage, irrigation, and fertilization choices in each of the 63 regions. The environmental consequences of all included management alternatives are estimated exogenously and known before ASMGHG is solved. Particularly, soil carbon and nitrous oxide emission levels are estimated with the Environmental Policy Integrated Climate (EPIC) model. Emissions from machinery operation, fertilizer and pesticide manufacturing, water pumping, and grain drying were also included. Details on data sources and emission computations are given in Schneider and McCarl (2005).

To understand ASMGHG's results let us qualitatively review how a climate policy affects crop management in ASMGHG. The introduction of a carbon price acts as a tax on agricultural emissions and a subsidy on emission reductions. There are two principal adjustments: a) production with less average emissions per hectare and b) production with more emissions per hectare on less land. The first possibility implies a more extensive agriculture using for example lower nitrogen inputs with a reduced tillage system. Under a more extensive system, the total cultivated (arable) area could even moderately increase. The second possibility implies a more intensive agriculture, where traditional field crops are managed more intensively to achieve a certain level of commodity supply using less land. The "spare" area can then be used for high carbon mitigation strategies such as afforestation or energy crop plantations. Which of the two strategies prevails depends on the mitigation benefits (carbon price) and costs including both direct strategy and opportunity cost.

Figure 1 summarizes the simulated responses to greenhouse gas emission incentives in absence of technical progress. As shown, the assumed degree of climate policy has considerable impact on preferred crop management. Lower carbon prices related to weaker climate policies lead to an increase in arable land with decreases in irrigation and nitrogen intensity but a slight increase in tillage intensity. Particularly, the highest land use increase amounts to 3.6% in absence of technical progress and at a carbon price of $40 per MgCE. Special mitigation measures such as afforestation and energy crop plantations are not yet economically attractive. Overall, small mitigation incentives lead to a more extensive agriculture. For carbon prices above $50 per mega gram carbon equivalent (MgCE), adaptation reverses. Traditional agriculture becomes more intensive, therefore requiring less land. Energy crop plantations and new forests become attractive.

Technical progress leads to a faster switch to more intensive agriculture combined with high carbon yielding mitigation measures (Figure 2). First, with technical progress land demand decreases and so does the amount occupied by traditional crops. In absence of a carbon policy, a 50% yield increase of all crops decreases the area occupied by traditional crops by 8.5%. As yields increase, the share of irrigation increases. This, however, reflects the assumption that all yields were increased by the same factor. Since the original irrigated yields were higher than the related non-irrigated yields, the absolute yield increase is higher for irrigated than for non-irrigated crops. The water use per hectare averaged over the entire area occupied by traditional crops (including irrigated and non-irrigated fields) increases with technical progress. The net effect of technical progress on total water requirements is ambiguous. For most cases, our results show a decrease in total water requirements. In some cases (technical progress on all crops), however, technical progress leads to an increase in total water use.

Mitigation Potentials

Does technical progress increase greenhouse gas emission mitigation potentials from agriculture? Intuitively, the answer is yes because technological progress saves costs. However, ASMGHG simulations show that decreases are possible (Table 1). At a carbon price of $50 per MgCE, a 10% increase in traditional crop yields decrease the total agricultural mitigation potential by 3 Terra grams. Higher yields for traditional crops induce two competing effects on bioenergy and afforestation potentials. On one hand, these mitigation options become cheaper because land rents are lower when yields are higher. On the other hand, higher yields for traditional crops increase the opportunity cost for afforestation and bioenergy. The net effect is ambiguous and as shown can result in a slight reduction of mitigation potential.

Table 1 also shows that emissions from traditional agriculture are relatively little impacted. In all cases, the absolute change in emission mitigation is below 10 Terra grams of carbon equivalents. Mitigation through bioenergy and afforestation, however, changes more dramatically. For example, at a carbon price of $50 per MgCE, a 10% yield increase on all crops more than doubles the mitigation contribution from this account. Only for low carbon prices, i.e. prices below $30 per MgCE, technical progress with traditional crops outweighs progress with energy crops in terms of total agricultural mitigation contribution. However, this difference is relatively small and does not exceed 4 Terra grams of carbon equivalent. On the other hand, increases in energy crop yields outperform progress on traditional crops by far. For carbon prices above $30 per MgCE, a 50% yield increase on energy crops increases total mitigation 3 to 7 times more than under a 50% yield increase on all traditional crops. A 10% yield increase has similar effects.

Furthermore, one should note that the achievable mitigation volume is not a linear function of technical progress and carbon price. Over a considerable range there is only a moderate increase in mitigation potential due to technical progress. Particularly, for yield increases up to 10 percent and for carbon prices below $50 per tce, agricultural mitigation potentials shift very little. Higher yields in combination with high carbon prices, on the other hand, may have a non-proportional, large shift in mitigation potentials. For example, at a carbon price of $40 per MgCE, a 50 percent yield increase in all crops increases the agricultural mitigation potential by about 100%.

Agricultural Emission Intensities

A common misperception is that agricultural mitigation efforts imply reduced emissions per hectare. However, relevant for climate change mitigation are changes in total emissions. As discussed above, there are two principal ways to mitigate through agriculture. First, emissions must be decreased if agriculture uses the same or somewhat increased land base. Second, greenhouse gas emissions could also be reduced with increasing emissions per hectare if they are accompanied by a sufficiently large decrease in the associated land requirement. In essences, the question is whether agriculture should produce more intensively on less land or more extensively on the same land?

Table 2 provides insight from ASMGHG simulations into this issue. In absence of technical progress, average emission intensities for traditional crop and livestock activities decrease from more than 800 kg CE per hectare to about 500 kg CE per hectare. Above a carbon price of $50 per MgCE, intensities remain fairly constant. If emission intensities are calculated over the combined area for agriculture, energy crops, and afforestation, we find a continuous decrease in emissions with a zero balance around $100 per MgCE and negative net emissions thereafter. Technical progress increases the bifurcation between traditional agriculture and energy crop production. Thus, higher yields lead to higher emission intensities for traditional agriculture but at the same time higher mitigation intensities for energy crops.

Traditional agriculture becomes more intensive regardless if technical progress involves traditional crops or energy crops. If the genetic yield potentials for traditional crops increase, so do the marginal factor productivities related to irrigation, fertilization, and tillage. Hence, a shift towards higher factor intensities is preferred. On the other hand, if only energy crop yields increase, opportunity costs for traditional agriculture would increase and the transition towards energy crops would occur earlier, i.e. at a lower mitigation incentive. As energy crops increase in area, traditional agricultural commodity prices increase and cause an incentive for increased factor intensities.

Market and Welfare Changes

Adaptations in land use and crop management affect agricultural markets. Supply shifts lead to changes in commodity prices and economic surplus. While, greenhouse gas mitigation incentives tend to increase prices for traditional agricultural commodities, the opposite effect takes place with technical progress. The magnitude of price and surplus changes depends on elasticities of supply and demand. Consumer surplus changes due to supply shifts are closely linked to price changes. In theory, technical progress may increase or decrease producer surplus depending on whether the increased commodities supply effect outweighs the decreased price effect. In practice, continuous technical progress in US agriculture has decreased the real farm income over many decades after World War II. The effect of climate policies on producer surplus is even more ambiguous. On one hand, carbon prices cause increasing production costs, reduced supply, and increasing prices for traditional agricultural commodities. On the other hand, additional surplus can be generated through bioenergy production.

Table 3 shows quantitative estimates of producer and consumer surplus changes from ASMGHG simulations. These changes only include welfare changes in agricultural markets but do not include impacts of environmental changes. In absence of technical progress, agricultural producer surplus decreases for carbon prices up to $80 per MgCE but increases at higher emission mitigation incentives. For relatively low carbon prices, producers don’t gain from technical progress. At higher carbon prices, this response reverses. Technical progress increases producer surplus. The strongest effect on producer surplus occurs under high carbon prices and high technical progress limited to energy crops. At higher carbon prices, progress on traditional crops seems to benefit producers more than progress on both traditional and energy crops. At lower carbon prices, exclusive progress on traditional crops hurts producers the most.

Consumers of agricultural commodities benefit from technical progress in traditional crops only for low or moderate carbon prices (Table 3). Higher emission mitigation incentives coupled with higher traditional crop yields lead to a higher share of energy crop plantations and thus may even increase prices for traditional agricultural commodities. The effect of increased energy crop yields is unambiguously negative for consumers across all carbon prices. The strongest negative impacts on consumers occur under high carbon prices and high technical progress limited to energy crops.

Conclusions

This study analyzes the costs of agricultural mitigation strategies and examines how technical progress and the intensity of climate policies affect land management adaptation. In absence of technical progress, we find for relatively modest carbon policies a shift towards a more extensive agriculture. This shift involves reduced fertilization and a smaller share of irrigated fields. The reduced emission intensity per hectare comes with a modest increase in total land under cultivation and an increase in tillage intensity. Stronger climate policies partially reverse this trend because energy crops and growing forests become an attractive, alternative land use option. However, additional forest and energy crop plantations are difficult to combine with an expanded area of traditional crops. The incentive and market price signals of stronger climate policies lead to a double strategy for agricultural lands. Non-food options with high carbon savings are combined with yield intensive agriculture on less land. Particularly, the share of irrigation increases. The optimal nitrogen intensity, however, is the outcome of a sensitive balancing act between N_2O and carbon emissions from nitrogen fertilizer use and emission offsets from additional energy crop plantations or forests made possible by higher yields with high fertilization.

The heterogeneous change of irrigation, tillage, and fertilization intensities across different carbon emission reduction incentives indicates a complex and non-linear nature of optimal land management responses to policies. This complex behavior can be simulated with data rich bottom-up models such as ASMGHG but may not be adequately captured with more general models, which condense management adaptations into a few constant substitution elasticities between agricultural inputs.

The interference between technical progress and agricultural adaptation to climate policies can be summarized in several points: First, the climate policy range, over which a more extensive agriculture is preferred, decreases as crop yields increase. This can be explained by the relatively inelastic demand for traditional agricultural products vs. perfectly elastic demand for carbon credits. Because higher yields require less land to produce the same output, marginal revenues for traditional commodities decline with technical progress while carbon revenues stay constant. Hence, technical progress decreases traditional cropland until marginal revenues are equal across all land management options. Second, our results show that technical progress on traditional crops hardly offers more mitigation benefits than progress with mitigation options themselves. Third, while agricultural producers benefit from technical progress with energy crops, they fare worse if technical progress improves traditional crops and low carbon prices. Depending on the income status of agricultural producers within society, the implied redistribution of welfare may or may not be welcome.

Several important limitations and uncertainties to this research should be noted. First, the findings presented here reflect technologies for which data were available to us. Second, most of the greenhouse gas emission data from the traditional agricultural sector are based on biophysical simulation models. Thus, the certainty of the estimates presented here depends on the quality of these models and the certainty of associated simulation model input data. Third, not internalized in this analysis were co-effects related to other agricultural externalities, costs or benefits of changed income distribution in the agricultural sector, and transaction costs of mitigation policies. Finally, all simulated results are derived from the optimal solution of the mathematical program and as such constitute point estimates without probability distribution.

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Table 1 Emission Mitigation and Changes due to Technical Progress [in TgCE]

Accounts	Carbon Price $/MgCE	Assumed Yield Increase 0%	All Crops 10%	All Crops 50%	Energy Crops 10%	Energy Crops 50%	Traditional Crops 10%	Traditional Crops 50%
Traditional Agriculture	0		+2	+3			+2	+3
	10	*52*		+4				+4
	20	*67*		+4				+4
	30	*75*	+3	+8		+2	+3	+7
	40	*85*		+6		+1		+5
	50	*96*	-2	+2		-1	-3	-2
	100	*112*		+2	+2	-1	+2	+2
	200	*122*	+2	+4		-6	+4	+6
	300	*138*	-1	-3	-2	-9	-1	+2
	500	*154*	+1	-3	-1	-8	+1	+1
Bioenergy and Afforestation	10			+8				
	20	*10*		+25		+4		+2
	30	*10*	+1	+87		+48		+5
	40	*10*	+4	+141	+4	+93	+1	+10
	50	*21*	+27	+183	+13	+129	-1	+20
	60	*43*	+32	+202	+23	+139	+6	+27
	70	*63*	+44	+203	+29	+157	+10	+37
	80	*92*	+37	+207	+28	+164	+4	+41
	90	*125*	+39	+210	+19	+153	+14	+32
	100	*139*	+42	+227	+29	+167	+11	+43
	125	*183*	+46	+234	+38	+181	+13	+33
	150	*209*	+57	+235	+40	+165	+14	+38
	200	*251*	+42	+221	+28	+154	+11	+36
	300	*273*	+48	+227	+30	+156	+14	+52
	500	*302*	+45	+220	+31	+153	+13	+53
All Accounts	0		+2	+3			+2	+3
	10	*52*		+12				+4
	20	*76*		+29		+4		+6
	30	*85*	+4	+95		+50	+3	+12
	40	*94*	+4	+147	+4	+94	+1	+15
	50	*117*	+25	+185	+13	+128	-3	+18
	60	*144*	+29	+202	+24	+140	+5	+24
	70	*166*	+44	+203	+30	+158	+11	+39
	80	*199*	+36	+207	+29	+161	+3	+41
	90	*235*	+41	+210	+19	+150	+16	+33
	100	*251*	+42	+228	+31	+166	+13	+46
	150	*329*	+55	+235	+41	+160	+16	+41
	200	*374*	+43	+225	+28	+148	+15	+42
	500	*456*	+46	+217	+30	+145	+15	+54

Table 2 Agricultural Emission Intensities and Additional Changes due to Technical Progress [in Kg CE/ha]

Accounts	Carbon Price	Assumed Yield Increase						
			All Crops		Energy Crops		Traditional Crops	
	$/MgCE	0%	10%	50%	10%	50%	10%	50%
Traditional Crop, Livestock	0	*816*	+2	+65			+2	+65
	10	*645*	+5	+54			+5	+55
	20	*592*	+3	+58		+2	+3	+54
	30	*562*	-4	+62		+9	-4	+45
	40	*533*	+8	+87	+3	+34	+6	+55
	50	*505*	+22	+112	+4	+50	+9	+71
	60	*498*	+30	+127	+7	+46	+16	+78
	80	*503*	+25	+135	+8	+72	+18	+67
	100	*510*	+23	+137	+5	+57	+6	+66
	200	*551*	+20	+132	+8	+62	+6	+68
	300	*517*	+37	+158	+8	+63	+39	+119
	500	*482*	+24	+141	+6	+43	+22	+128
Crop, Livestock, Bioenergy, Afforestation	10	*645*	+5	21			+5	+55
	20	*559*	+3	-43		-11	+3	+40
	30	*529*	-6	-270		-156	-5	+20
	40	*499*	-8	-438	-13	-285	+2	+9
	50	*432*	-75	-554	-42	-383	11	-20
	60	*345*	-86	-601	-72	-412	-10	-48
	70	*280*	-129	-602	-89	-457	-28	-101
	80	*181*	-106	-611	-85	-461	-5	-116
	90	*74*	-118	-618	-54	-424	-46	-95
	100	*28*	-120	-668	-88	-464	-37	-136
	125	*-115*	-124	-669	-99	-482	-36	-105
	150	*-189*	-154	-682	-114	-440	-47	-130
	200	*-315*	-122	-648	-77	-405	-45	-137
	300	*-420*	-133	-650	-73	-398	-43	-177
	500	*-546*	-134	-634	-79	-393	-48	-185

Table 3 Economic Surplus Changes due to Carbon Price and Additional Changes due to Technical Progress [in Mill $]

Accounts	Carbon Price $/MgCE	Assumed Yield Increase						
			All Crops		Energy Crops		Traditional Crops	
		0%	10%	50%	10%	50%	10%	50%
Producer Surplus Change	0		-3	-11			-3	-11
	10	*-3*	-3	-10	-3	-3	-6	-13
	20	*-5*	-3	-8	-5	-4	-8	-15
	30	*-7*	-3	-4	-7	-3	-10	-16
	40	*-8*	-2	+1	-7		-10	-16
	50	*-8*		+7	-7	+6	-10	-15
	60	*-7*	+1	+10	-4	+10	-9	-13
	70	*-4*	+2	+12		+18	-7	-11
	80	*-1*	+2	+14	+3	+22	-3	-8
	90	*3*	+2	+16	+8	+27		-5
	100	*7*	+2	+16	+11	+34	+4	-1
	125	*15*	+2	+24	+21	+50	+12	+6
	150	*25*	+3	+27	+32	+66	+21	+15
	200	*46*	+4	+35	+55	+98	+40	+33
	300	*87*	+11	+57	+101	+163	+83	+72
	400	*130*	+14	+77	+151	+229	+125	+113
	500	*172*	+18	+97	+197	+296	+168	+152
Consumer Surplus Change	0		+9	+31			+9	+31
	10		+9	+30			+9	+31
	20		+9	+29			+9	+31
	30		+9	+26		-3	+9	+29
	40	*-1*	+8	+23	-2	-7	+7	+28
	50	*-3*	+6	+19	-4	-13	+5	+25
	60	*-5*	+6	+19	-7	-17	+2	+22
	70	*-9*	+5	+19	-12	-24		+19
	80	*-13*	+5	+20	-16	-28	-6	+16
	90	*-18*	+7	+21	-21	-32	-9	+12
	100	*-23*	+7	+22	-25	-38	-13	+9
	125	*-30*	+7	+22	-34	-50	-21	+3
	150	*-40*	+8	+25	-44	-61	-29	-4
	200	*-59*	+9	+29	-63	-83	-45	-15
	300	*-91*	+8	+30	-97	-124	-77	-40
	400	*-122*	+9	+33	-131	-161	-106	-64
	500	*-151*	+10	+36	-161	-200	-133	-84

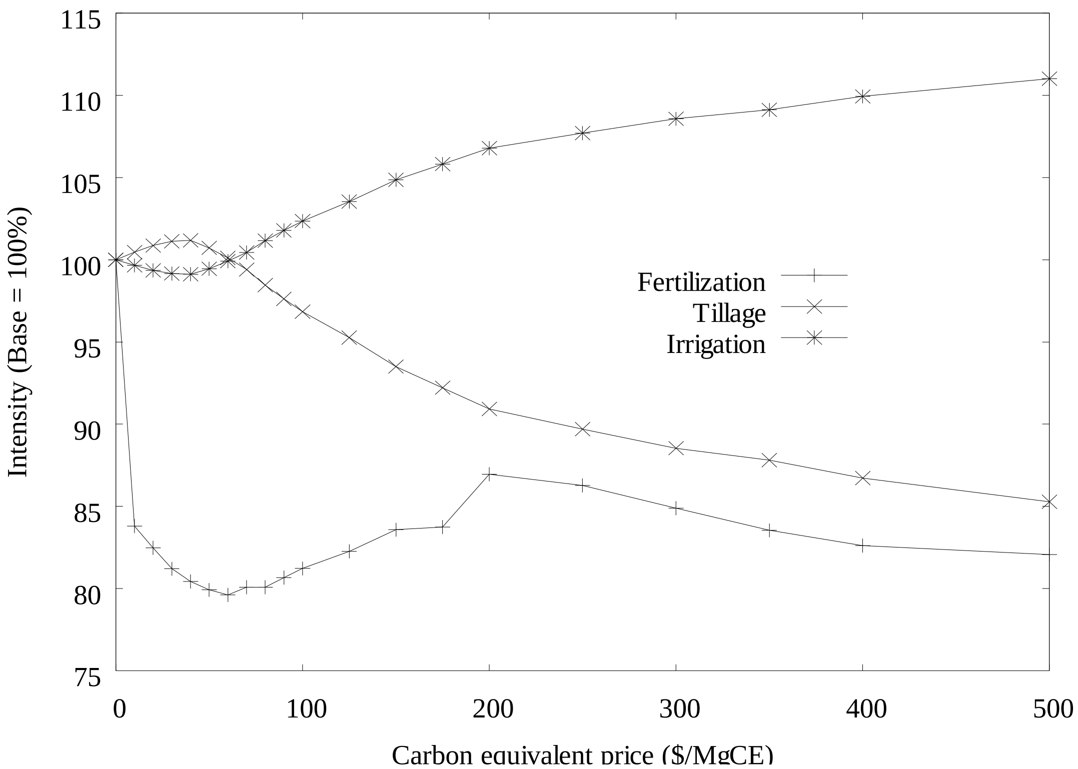

Figure 1 Adaptation of Crop Management under Climate Policy without Technical Progress

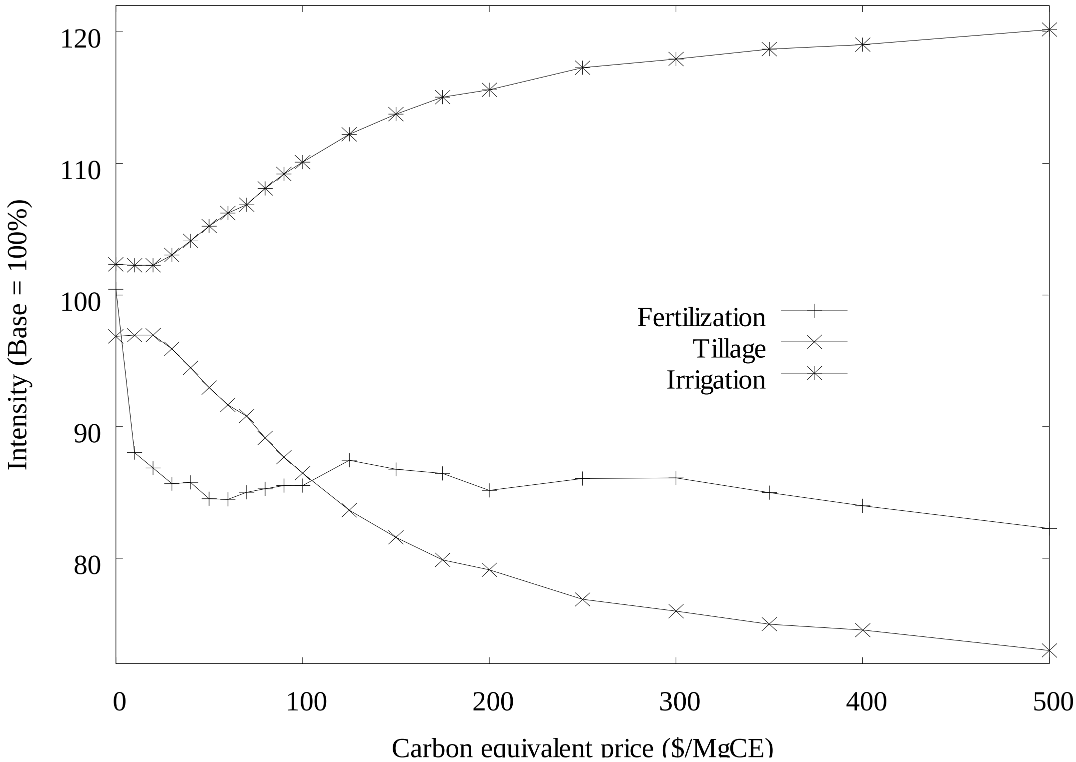

Figure 2 Adaptation of Crop Management under Climate Policy and 50% Yield Increases for all Crops

Appendix

Agricultural Prices Indexes

Yield Increase	Carbon Price in $/MgCE	Livestock			Field Crops		
		Yield Increase assumed for					
		All Crops	Energy Crops	Annual Crops	All Crops	Energy Crops	Annual Crops
0PCT	0	1.00	1.00	1.00	1.00	1.00	1.00
	10	1.00	1.00	1.00	0.99	0.99	0.99
	20	1.00	1.00	1.00	0.98	0.98	0.98
	30	1.01	1.01	1.01	0.97	0.97	0.97
	40	1.03	1.03	1.03	0.97	0.97	0.97
	50	1.05	1.05	1.05	0.99	0.99	0.99
	60	1.08	1.08	1.08	1.02	1.02	1.02
	70	1.13	1.13	1.13	1.06	1.06	1.06
	80	1.17	1.17	1.17	1.10	1.10	1.10
	90	1.21	1.21	1.21	1.16	1.16	1.16
	100	1.27	1.27	1.27	1.21	1.21	1.21
	125	1.34	1.34	1.34	1.32	1.32	1.32
	150	1.48	1.48	1.48	1.43	1.43	1.43
	175	1.55	1.55	1.55	1.55	1.55	1.55
	200	1.66	1.66	1.66	1.67	1.67	1.67
	250	1.83	1.83	1.83	1.89	1.89	1.89
	300	2.03	2.03	2.03	2.15	2.15	2.15
	350	2.26	2.26	2.26	2.40	2.40	2.40
	400	2.45	2.45	2.45	2.64	2.64	2.64
	500	2.84	2.84	2.84	3.10	3.10	3.10
1%	0	1.00	1.00	1.00	1.00	1.00	1.00
	10	1.01	1.00	1.01	0.99	0.99	0.99
	20	1.01	1.00	1.01	0.99	0.98	0.99
	30	1.02	1.01	1.02	0.98	0.97	0.98
	40	1.03	1.03	1.03	0.98	0.97	0.98
	50	1.05	1.05	1.05	1.00	0.99	1.00
	60	1.08	1.08	1.08	1.03	1.02	1.02
	70	1.13	1.13	1.13	1.07	1.06	1.06
	80	1.17	1.17	1.17	1.11	1.11	1.10
	90	1.22	1.22	1.22	1.17	1.16	1.16
	100	1.28	1.27	1.28	1.22	1.22	1.22
	125	1.36	1.36	1.35	1.33	1.33	1.32
	150	1.50	1.48	1.50	1.45	1.44	1.44
	175	1.55	1.55	1.55	1.57	1.56	1.55
	200	1.67	1.67	1.66	1.69	1.68	1.67
	250	1.84	1.83	1.84	1.91	1.90	1.89
	300	2.04	2.03	2.04	2.16	2.16	2.15

	350	2.28	2.27	2.28	2.41	2.42	2.39
	400	2.48	2.46	2.47	2.69	2.66	2.67
	500	2.87	2.85	2.87	3.15	3.13	3.14
	0	1.00	1.00	1.00	1.00	1.00	1.00
	10	1.01	1.00	1.01	1.00	0.99	1.00
	20	1.02	1.00	1.02	0.99	0.98	0.99
	30	1.02	1.01	1.02	0.98	0.97	0.98
	40	1.03	1.03	1.03	0.98	0.97	0.98
	50	1.06	1.05	1.06	0.99	0.99	0.99
	60	1.09	1.08	1.09	1.03	1.02	1.02
	70	1.14	1.13	1.13	1.07	1.06	1.06
	80	1.18	1.17	1.18	1.12	1.11	1.10
2%	90	1.23	1.22	1.22	1.18	1.17	1.16
	100	1.29	1.28	1.28	1.22	1.22	1.22
	125	1.36	1.36	1.35	1.34	1.33	1.32
	150	1.51	1.48	1.50	1.45	1.44	1.43
	175	1.56	1.55	1.56	1.57	1.57	1.55
	200	1.68	1.67	1.67	1.70	1.69	1.68
	250	1.85	1.84	1.85	1.92	1.92	1.90
	300	2.05	2.03	2.05	2.16	2.17	2.14
	350	2.30	2.28	2.29	2.44	2.43	2.40
	400	2.49	2.47	2.48	2.71	2.68	2.67
	500	2.89	2.86	2.87	3.18	3.15	3.14
	0	1.00	1.00	1.00	1.00	1.00	1.00
	10	1.02	1.00	1.02	1.00	0.99	1.00
	20	1.03	1.00	1.03	0.99	0.98	0.99
	30	1.04	1.01	1.04	0.99	0.97	0.99
	40	1.05	1.03	1.05	0.99	0.97	0.99
	50	1.07	1.05	1.07	1.00	0.99	1.00
	60	1.12	1.09	1.12	1.04	1.03	1.03
	70	1.16	1.14	1.13	1.08	1.08	1.06
	80	1.21	1.17	1.21	1.14	1.13	1.11
5%	90	1.26	1.23	1.24	1.19	1.19	1.17
	100	1.32	1.28	1.30	1.24	1.23	1.21
	125	1.38	1.37	1.37	1.35	1.35	1.32
	150	1.53	1.48	1.52	1.47	1.46	1.43
	175	1.58	1.56	1.56	1.59	1.62	1.54
	200	1.70	1.68	1.70	1.72	1.72	1.68
	250	1.89	1.85	1.88	1.97	1.96	1.91
	300	2.10	2.04	2.08	2.23	2.21	2.16
	350	2.35	2.29	2.33	2.51	2.49	2.43
	400	2.54	2.49	2.52	2.75	2.74	2.68
	500	2.96	2.88	2.92	3.27	3.21	3.18
	0	1.00	1.00	1.00	1.00	1.00	1.00
10%	10	1.00	1.00	1.00	0.99	0.99	0.99
	20	1.01	1.00	1.01	0.98	0.98	0.98

	30	1.01	1.01	1.01	0.98	0.97	0.97
	40	1.04	1.04	1.03	0.99	0.98	0.99
	50	1.08	1.06	1.06	1.02	1.00	1.00
	60	1.13	1.09	1.10	1.06	1.05	1.03
	70	1.19	1.15	1.14	1.11	1.10	1.06
	80	1.22	1.18	1.21	1.16	1.16	1.12
	90	1.26	1.24	1.23	1.21	1.21	1.16
	100	1.32	1.28	1.29	1.26	1.26	1.20
	125	1.37	1.39	1.37	1.36	1.37	1.32
	150	1.53	1.48	1.50	1.50	1.50	1.42
	175	1.58	1.57	1.57	1.61	1.64	1.54
	200	1.70	1.69	1.68	1.75	1.76	1.66
	250	1.90	1.87	1.87	2.02	2.01	1.90
	300	2.12	2.07	2.12	2.32	2.28	2.18
	350	2.36	2.32	2.33	2.59	2.58	2.45
	400	2.55	2.52	2.50	2.85	2.84	2.69
	500	2.96	2.90	2.92	3.35	3.32	3.17
	0	1.00	1.00	1.00	1.00	1.00	1.00
	10	1.00	1.00	1.00	0.98	0.99	0.98
	20	1.02	1.00	1.02	0.98	0.98	0.98
	30	1.04	1.01	1.02	0.98	0.97	0.97
	40	1.07	1.04	1.05	1.00	0.99	0.98
	50	1.13	1.08	1.08	1.05	1.03	0.99
	60	1.19	1.12	1.13	1.11	1.09	1.03
	70	1.24	1.17	1.18	1.16	1.15	1.08
	80	1.27	1.22	1.23	1.20	1.20	1.13
20%	90	1.32	1.28	1.28	1.28	1.26	1.18
	100	1.38	1.30	1.30	1.33	1.33	1.21
	125	1.44	1.42	1.43	1.44	1.45	1.34
	150	1.58	1.48	1.53	1.57	1.60	1.44
	175	1.66	1.60	1.66	1.71	1.73	1.58
	200	1.78	1.70	1.73	1.87	1.85	1.67
	250	1.98	1.91	1.94	2.16	2.14	1.93
	300	2.25	2.12	2.19	2.45	2.44	2.20
	350	2.46	2.32	2.37	2.74	2.74	2.43
	400	2.64	2.56	2.62	2.96	2.99	2.70
	500	3.12	2.95	3.03	3.53	3.54	3.14
	0	1.00	1.00	1.00	1.00	1.00	1.00
	10	1.01	1.00	1.00	0.99	0.99	0.99
	20	1.05	1.02	1.01	1.00	0.99	0.98
	30	1.10	1.05	1.04	1.04	1.01	0.98
50%	40	1.18	1.09	1.07	1.09	1.06	0.99
	50	1.25	1.15	1.12	1.17	1.14	1.01
	60	1.29	1.19	1.18	1.22	1.20	1.04
	70	1.36	1.27	1.23	1.27	1.29	1.08
	80	1.39	1.28	1.29	1.33	1.35	1.12

90	1.45	1.32	1.35	1.41	1.40	1.17
100	1.49	1.38	1.38	1.47	1.47	1.23
125	1.63	1.47	1.49	1.63	1.64	1.32
150	1.69	1.59	1.60	1.80	1.80	1.42
175	1.84	1.70	1.69	1.95	1.97	1.52
200	1.91	1.81	1.84	2.11	2.15	1.65
250	2.21	1.99	2.07	2.47	2.48	1.88
300	2.43	2.27	2.26	2.77	2.84	2.10
350	2.66	2.49	2.53	3.09	3.17	2.36
400	2.94	2.74	2.73	3.44	3.50	2.59
500	3.38	3.14	3.14	4.04	4.21	3.03

Land Use Changes (in 1000 acres)

Yield Increase	Carbon Price in $/MgCE	Arable Cropland			Afforested Land			Energy Crop Plantations			Total		
		Yield Increase assumed for:											
		All Crops	Energy Crops	Annual Crops	All Crops	Energy Crops	Annual Crops	All Crops	Energy Crops	Annual Crops	All Crops	Energy Crops	Annual Crops
0%	0	319973	319973	319973	0	0	0	0	0	0	319973	319973	319973
	10	324388	324388	324388	0	0	0	0	0	0	324388	324388	324388
	20	328396	328396	328396	2583	2583	2583	0	0	0	330979	330979	330979
	30	330958	330958	330958	2583	2583	2583	1	1	1	333541	333541	333541
	40	331555	331555	331555	2583	2583	2583	37	37	37	334174	334174	334174
	50	327008	327008	327008	2583	2583	2583	4926	4926	4926	334516	334516	334516
	60	321075	321075	321075	3532	3532	3532	14045	14045	14045	338652	338652	338652
	70	314397	314397	314397	3532	3532	3532	22820	22820	22820	340749	340749	340749
	80	305910	305910	305910	4673	4673	4673	34039	34039	34039	344622	344622	344622
	90	298807	298807	298807	8520	8520	8520	41668	41668	41668	348995	348995	348995
	100	292566	292566	292566	8647	8647	8647	48624	48624	48624	349838	349838	349838
	125	280539	280539	280539	9755	9755	9755	65466	65466	65466	355760	355760	355760
	150	268200	268200	268200	9755	9755	9755	78540	78540	78540	356496	356496	356496
	175	259873	259873	259873	9755	9755	9755	88254	88254	88254	357883	357883	357883
	200	252005	252005	252005	9755	9755	9755	96033	96033	96033	357794	357794	357794
	250	245003	245003	245003	9755	9755	9755	102466	102466	102466	357225	357225	357225
	300	238692	238692	238692	9755	9755	9755	107783	107783	107783	356231	356231	356231
	350	234900	234900	234900	9755	9755	9755	112513	112513	112513	357168	357168	357168
	400	229446	229446	229446	9755	9755	9755	118643	118643	118643	357844	357844	357844
	500	222595	222595	222595	9755	9755	9755	123793	123793	123793	356144	356144	356144
1 %	0	318765	319973	318765	0	0	0	0	0	0	318765	319973	318765

	10	324053	324388	324053	0	0	0	0	0	0	324053	324388	324053
	20	327803	328396	327803	2583	2583	2583	0	0	0	330386	330979	330386
	30	331003	330958	331003	2583	2583	2583	1	1	1	333587	333541	333587
	40	331746	331555	331746	2583	2583	2583	37	37	37	334365	334174	334365
	50	326399	326948	326372	2583	2583	2583	5286	5155	5141	334268	334686	334096
	60	319413	320904	319801	3532	3532	3532	15040	14588	14521	337985	339024	337854
	70	313548	313973	313991	3532	3532	3532	24160	23447	23102	341240	340952	340624
	80	304621	305465	305019	4440	4612	4427	35549	34860	34632	344609	344937	344078
	90	297080	298238	297504	8502	8324	8487	43303	42552	42649	348885	349114	348640
	100	291678	292290	291849	8647	8647	8647	49505	49092	49017	349830	350030	349514
	125	277569	278707	280726	9755	9755	9755	68488	67294	65098	355813	355757	355580
	150	266391	266550	266830	9755	9755	9755	80288	80203	79765	356434	356508	356351
	175	257822	258795	258744	9755	9755	9755	90252	89608	89359	357830	358159	357859
	200	250760	251692	251676	9755	9755	9755	97153	96394	96102	357668	357842	357533
	250	243335	244902	243565	9755	9755	9755	103875	102788	103625	356965	357446	356946
	300	237046	238582	237214	9755	9755	9755	108896	107886	108727	355697	356223	355696
	350	233276	234617	233102	9755	9755	9755	114058	112876	113230	357090	357248	356088
	400	228550	229344	228712	9755	9755	9755	119833	118780	119564	358138	357880	358032
	500	221222	222547	220549	9755	9755	9755	124925	124073	124586	355903	356376	354891
	0	318135	319973	318135	0	0	0	0	0	0	318135	319973	318135
	10	323588	324388	323588	0	0	0	0	0	0	323588	324388	323588
	20	327234	328396	327234	2583	2583	2583	0	0	0	329816	330979	329816
	30	330801	330958	330801	2583	2583	2583	1	1	1	333384	333541	333384
	40	332261	331525	332261	2583	2583	2583	41	41	41	334884	334148	334884
2%	50	326204	326999	326167	2583	2583	2583	5601	5569	5023	334387	335150	333773
	60	317708	320481	318724	3532	3532	3532	16331	15169	14785	337571	339182	337041
	70	312140	314089	312948	3532	3532	3532	24726	24119	23600	340398	341740	340080
	80	302579	305091	304192	3847	4666	4442	37606	35500	34663	344032	345256	343298
	90	295055	297620	296401	8517	8236	8515	45247	43341	43568	348819	349197	348484
	100	289892	292029	290889	8647	8647	8647	51330	49452	49471	349869	350129	349007
	125	275477	276315	279087	9755	9755	9755	70387	69962	66391	355619	356032	355234

	150	264681	266068	265314	9755	9755	9755	81996	80871	81134	356432	356695	356203
	175	256261	257979	257333	9755	9755	9755	91806	90429	90706	357823	358164	357794
	200	249186	251387	251471	9755	9755	9755	98612	96705	96300	357554	357847	357526
	250	241582	244770	241840	9755	9755	9755	105221	102928	104934	356558	357453	356529
	300	235790	238469	235961	9755	9755	9755	109769	108084	109366	355314	356309	355082
	350	231610	234814	231480	9755	9755	9755	116115	114106	114463	357480	358676	355698
	400	226439	229517	226884	9755	9755	9755	121134	118933	120537	357329	358205	357176
	500	219557	222681	219238	9755	9755	9755	125925	124253	125496	355237	356690	354489
	0	316170	319973	316170	0	0	0	0	0	0	316170	319973	316170
	10	321602	324388	321602	0	0	0	0	0	0	321602	324388	321602
	20	327842	328396	327842	2583	2583	2583	0	0	0	330424	330979	330424
	30	330359	330958	330395	2583	2583	2583	37	1	1	332979	333541	332979
	40	330534	331525	331233	2583	2583	2583	1107	41	41	334223	334148	333857
	50	325800	326954	329172	2583	2583	2583	5973	5870	3761	334355	335406	335516
	60	313249	319163	316308	3532	3188	3532	19846	17060	15762	336626	339411	335602
	70	307127	312188	310253	3532	3532	3532	29402	26317	25479	340060	342037	339264
	80	296607	301432	301848	3647	3911	3807	43708	40716	35755	343962	346058	341409
5%	90	291360	295294	293131	8238	7567	8468	48906	46407	45773	348503	349268	347371
	100	286766	289661	288456	8647	8647	8647	54712	52375	51368	350126	350684	348471
	125	272474	274919	274563	9755	9755	9755	73144	71581	70677	355373	356255	354996
	150	259803	264835	263458	9755	9755	9755	86981	82919	83078	356540	357510	356291
	175	251598	256324	254438	9755	9755	9755	96454	92111	93534	357808	358191	357728
	200	247180	249878	248788	9755	9755	9755	100597	98339	98799	357532	357972	357342
	250	237008	244575	236940	9755	9755	9755	109224	103336	108045	355987	357667	354740
	300	230568	238604	231587	9755	9755	9755	114359	108744	111883	354683	357103	353225
	350	227206	233968	226737	9755	9755	9755	120449	115281	116672	357410	359004	353164
	400	222494	228882	221634	9755	9755	9755	124699	119985	122513	356948	358623	353902
	500	215384	222543	214925	9755	9755	9755	129179	124894	128364	354318	357192	353044
	0	317009	319973	317009	0	0	0	0	0	0	317009	319973	317009
10%	10	322045	324388	322045	0	0	0	0	0	0	322045	324388	322045
	20	327393	328396	327393	2583	2583	2583	0	0	0	329976	330979	329976

	30	327923	330901	328054	2583	2583	2583	247	37	36	330753	333521	330673
	40	327201	330016	327433	2583	2583	2583	1815	1774	466	331598	334372	330481
	50	317836	324416	326061	2583	2583	2583	15591	9881	4568	336009	336879	333211
	60	308501	315667	314695	3177	3200	3532	26508	22738	16694	338186	341605	334920
	70	298523	307067	305502	3532	3532	3532	39444	33117	27199	341498	343716	336232
	80	291870	298417	297958	3532	3532	3889	49048	44901	37930	344450	346849	339778
	90	285693	292603	289262	8499	6480	8647	55041	49980	48412	349233	349063	346321
	100	279239	286673	284971	8647	8647	8647	62122	56694	53798	350009	352014	347416
	125	266071	271317	271354	9755	9755	9755	79261	75808	72185	355087	356881	353294
	150	252051	261370	257941	9755	9755	9755	94278	87173	85395	356085	358298	353092
	175	246273	252876	246293	9755	9755	9755	101083	95592	97712	357112	358224	353761
	200	240369	248926	242690	9755	9755	9755	106083	99602	101853	356207	358283	354298
	250	228416	243726	228873	9755	9755	9755	115792	105320	112814	353964	358802	351443
	300	223938	238538	224304	9755	9755	9755	121693	111538	116722	355386	359832	350781
	350	220014	232545	219487	9755	9755	9755	125544	117035	121145	355313	359335	350387
	400	215798	227722	214151	9755	9755	9755	129920	121593	125834	355474	359071	349740
	500	209505	222362	210160	9755	9755	9755	134502	126708	131856	353762	358825	351771
	0	312778	319973	312778	0	0	0	0	0	0	312778	319973	312778
	10	314848	324388	314848	0	0	0	0	0	0	314848	324388	314848
	20	317085	328396	317076	2583	2583	2583	407	1	0	320075	330979	319658
	30	319786	330601	321098	2583	2583	2583	1792	231	191	324161	333415	323872
	40	315895	327173	321459	2583	2583	2583	12101	5295	1575	330578	335050	325617
	50	305082	316207	319229	2583	2583	2583	27208	20457	5245	334873	339247	327057
20%	60	293327	309172	309991	2717	2604	3532	42257	30547	17352	338301	342323	330875
	70	286965	298989	297864	3364	3532	3532	52221	43085	30889	342550	345605	332284
	80	281997	293094	287658	3532	3532	4533	58307	50940	45392	343836	347566	337583
	90	273918	286103	284595	8479	6443	8647	68985	57660	51344	351382	350206	344586
	100	265697	277138	281405	8647	8282	9047	76577	69066	55780	350921	354486	346231
	125	251715	266340	264393	9755	9755	9755	91509	81481	74274	352979	357576	348422
	150	238715	256434	249655	9755	9755	9755	103736	92799	88744	352206	358989	348154
	175	230168	250079	240314	9755	9755	9755	114028	98793	99529	353952	358628	349599

	200	224051	247425	230185	9755	9755	9755	119210	102250	108428	353017	359431	348368
	250	214865	242406	218289	9755	9755	9755	128018	108737	119176	352639	360899	347220
	300	211800	234245	210740	9755	9755	9755	130032	116432	125516	351587	360432	346012
	350	207620	228861	206325	9755	9755	9755	134676	120880	129570	352051	359497	345650
	400	203003	226734	202538	9755	9755	9755	137940	123471	132975	350698	359961	345269
	500	199906	221495	198691	9755	9755	11562	143332	128421	135253	352993	359672	345507
	0	292761	319973	292761	0	0	0	0	0	0	292761	319973	292761
	10	293442	324390	293878	0	0	0	2564	1	0	296007	324391	293878
	20	293462	327364	294689	2583	2583	2583	7275	1112	1110	303319	331059	298381
	30	285398	321409	294906	2583	2583	2583	26923	14491	2320	314903	338482	299809
	40	274952	310382	292120	2583	2583	2583	43997	28288	4742	321532	341253	299445
	50	264755	299068	289814	2583	2583	2583	61349	42831	13893	328687	344482	306290
	60	256444	292479	281112	2583	2583	3532	73987	53613	26610	333014	348674	311254
	70	251378	282164	272824	2583	2638	3532	80024	66033	40875	333985	350835	317231
	80	241941	273071	269104	3205	3218	6376	90840	76492	50590	335986	352781	326070
50%	90	234265	268354	263587	6371	4427	8647	98701	82558	57852	339336	355339	330087
	100	228299	264914	255302	8203	6458	9165	104779	86680	68843	341282	358052	333310
	125	215367	251780	243721	9755	9755	9755	119970	98955	82313	345092	360490	335789
	150	206875	249236	232665	9755	9755	9755	130901	102492	97426	347531	361483	339846
	175	200269	243568	223716	9755	9755	9755	137466	108256	107799	347490	361580	341271
	200	197515	236992	214828	9755	9755	9755	142961	114950	117018	350232	361697	341601
	250	189693	230885	198071	9755	9755	9755	149513	121077	135314	348962	361718	343141
	300	186784	228830	190772	9755	9755	9755	152885	123212	140470	349425	361797	340997
	350	183625	224810	184329	9755	9755	9755	156435	127054	146187	349816	361620	340271
	400	182199	222743	179709	9755	9755	9755	158871	129147	150610	350824	361646	340075
	500	177574	219507	173732	9755	9755	12848	161073	132564	152906	348402	361827	339485