# THE EFFECTS OF OZONE ON COLORADO AGRICULTURE

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The purpose of this note is to provide an overview of the biological effects of ozone on agricultural activities of importance to Colorado and some preliminary estimates of the economic benefits of reducing ozone concentrations.

The harmful effects of air pollution on human health have been the main focus of the state's efforts to reduce leaks from gas and oil drilling and distribution. But leaks that release volatile organic compounds (VOCs) and contribute to high ozone levels are also detrimental to plant and animal growth with negative effects on farm incomes and the rural economy. Passing regulations that result in reduced ground level ozone could conservatively have the impacts of a five percent increase in crop and livestock production resulting in a more than $300 million increase in agricultural income annually in Colorado.

## Creation of ozone and its sources

Ozone ($O_3$) is an unstable molecule consisting of 3 oxygen atoms. The third oxygen atom easily disassociates from the molecule and combines with other compounds in a process called oxidation. Tropospheric (near ground level) ozone is created when ultraviolet radiation and high temperatures facilitate complex photochemical reactions involving oxides of nitrogen (NOx; a single nitrogen atom with one or two oxygen atoms[1]) and VOCs. NOx are produced during combustion at high temperatures when nitrogen is present, such as in vehicle engines; by lightning strikes, and agricultural uses of nitrogenous fertilizers. VOCs are produced naturally by woody vegetation. They are also present in oil and natural gas underground and leaks from drilling and pipelines are another major source of VOCs (natural gas is 70 to 90 percent methane with the remainder being mostly ethane, propane, and butane). In most locations, the availability of NOx from fuel-efficient engines does not constrain the conversion of VOCs to $O_3$.

Table 1 reports an inventory of VOC sources for the whole state and for selected counties for 2011. For the state as a whole, almost 1.3 million tons of VOCs were emitted in 2011. Almost 70 percent of these emissions were from biogenic sources (various natural sources). Oil and gas sources are 17 percent of the total VOC emissions but 54 percent of the non-biogenic sources. Oil and gas contributions to total VOC emissions are dramatically higher for three of the counties included in the table; Garfield (54 percent), Rio Blanco (46 percent), and Weld (78 percent).

Table 2 shows an inventory of sources of NOx and VOC for Mesa County, collected as part of the 2010 Colorado Air Pollutant Emissions Inventory. Vehicles are the largest single source of NOx (2,506 tons), with oil and gas point and area sources a close second (2,389 tons). By far, the largest source of VOCs is biogenic (30,300 tons; almost 77 percent of the total). Oil and gas sources of VOCs account for about 11 percent of the total and vehicles 6.6 percent. [2]

[1] Note that nitrogen oxides (NO and $NO_2$) differ from nitrous oxide ($N_2O$), which is an extremely potent greenhouse gas.
[2] Methane ($CH_4$) is both a potent greenhouse gas and a precursor of ozone. In some contexts, methane is considered a VOC. The chemical process that converts methane to ozone is qualitatively similar to that of other VOCs but typically is slower. In the Colorado air pollutant emissions inventory methane is not included as a VOC.

### Table 1. Sources of VOCs for Colorado and selected counties, 2011 (tons per year)

| Category 2011 | State | Delta | Dolores | Garfield | Mesa | Moffat | Montrose | Ouray | Rio Blanco | San Miguel | Weld |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Agriculture** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Aircraft** | 1,238 | 27 | 0 | 6 | 5 | 1 | 12 | 0 | 16 | 0 | 91 |
| **Biogenic** | 880,531 | 16,547 | 13,923 | 27,966 | 30,300 | 28,263 | 19,255 | 8,683 | 29,101 | 11,830 | 19,927 |
| **Commercial Cooking** | 182 | 1 | 0 | 2 | 5 | 0 | 1 | 0 | 0 | 0 | 9 |
| **Construction** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Forest and Prescribed Fire** | 7,252 | 88 | 13 | 149 | 286 | 47 | 601 | 64 | 101 | 33 | 777 |
| **Fuel Combustion** | 534 | 45 | 1 | 8 | 17 | 14 | 17 | 1 | 3 | 1 | 19 |
| **Highway Vehicles** | 61,219 | 305 | 55 | 1,076 | 2,456 | 272 | 707 | 112 | 175 | 151 | 3,100 |
| **Non-Road** | 29,876 | 243 | 341 | 314 | 629 | 179 | 239 | 254 | 312 | 231 | 1,182 |
| **O&G area** | 62,362 | 2 | 728 | 20,080 | 2,335 | 830 | 0 | 0 | 3,640 | 133 | 15,120 |
| **O&G points** | 22,152 | 1 | 125 | 6,374 | 864 | 2,033 | 10 | 0 | 3,278 | 208 | 6,181 |
| **O&G Condensate Tanks** | 125,800 | 0 | 113 | 9,284 | 330 | 1,262 | 0 | 0 | 18,326 | 85 | 85,060 |
| **Other Point Sources** | 14,740 | 46 | 0 | 212 | 503 | 165 | 102 | 0 | 9 | 2 | 1,762 |
| **Pesticide Application** | 14,703 | 49 | 149 | 18 | 31 | 15 | 61 | 59 | 8 | 60 | 860 |
| **Portable Fuel Containers** | 3,640 | 11 | 1 | 31 | 77 | 6 | 15 | 4 | 7 | 11 | 188 |
| **Railroads** | 770 | 17 | 0 | 29 | 53 | 7 | 0 | 0 | 0 | 0 | 61 |
| **Road Dust** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Solvent Utilization** | 21,575 | 128 | 9 | 237 | 623 | 57 | 173 | 18 | 29 | 32 | 1,089 |
| **Structure Fires** | 58 | 0 | 0 | 1 | 2 | 0 | 0 | 0 | 0 | 0 | 3 |
| **Surface Coating** | 6,001 | 36 | 2 | 66 | 173 | 16 | 48 | 5 | 8 | 9 | 303 |
| **Tank Trucks In Transit** | 70 | 0 | 0 | 1 | 2 | 0 | 0 | 0 | 0 | 0 | 3 |
| **Wood burning** | 16,906 | 462 | 31 | 791 | 636 | 204 | 205 | 74 | 111 | 133 | 275 |
| TOTAL | 1,269,608 | 18,009 | 15,491 | 66,643 | 39,327 | 33,372 | 21,448 | 9,275 | 55,123 | 12,918 | 136,010 |
| **from oil and gas** | 210,314 | 3 | 966 | 35,738 | 3,530 | 4,125 | 10 | 0 | 25,243 | 426 | 106,361 |
| **oil and gas share of total** | 0.17 | 0.00 | 0.06 | 0.54 | 0.09 | 0.12 | 0.00 | 0.00 | 0.46 | 0.03 | 0.78 |
| **Oil and gas as share of nonbiogenic sources** | 0.54 | 0.00 | 0.62 | 0.92 | 0.39 | 0.81 | 0.00 | 0.00 | 0.97 | 0.39 | 0.92 |

Source: Personal Communication, Dale Wells, Air Pollution Control Division, Colorado Department of Public Health and Environment.

**Table 2. Inventory of NOx and VOC emission sources for Mesa County, 2010 (tons per year)**

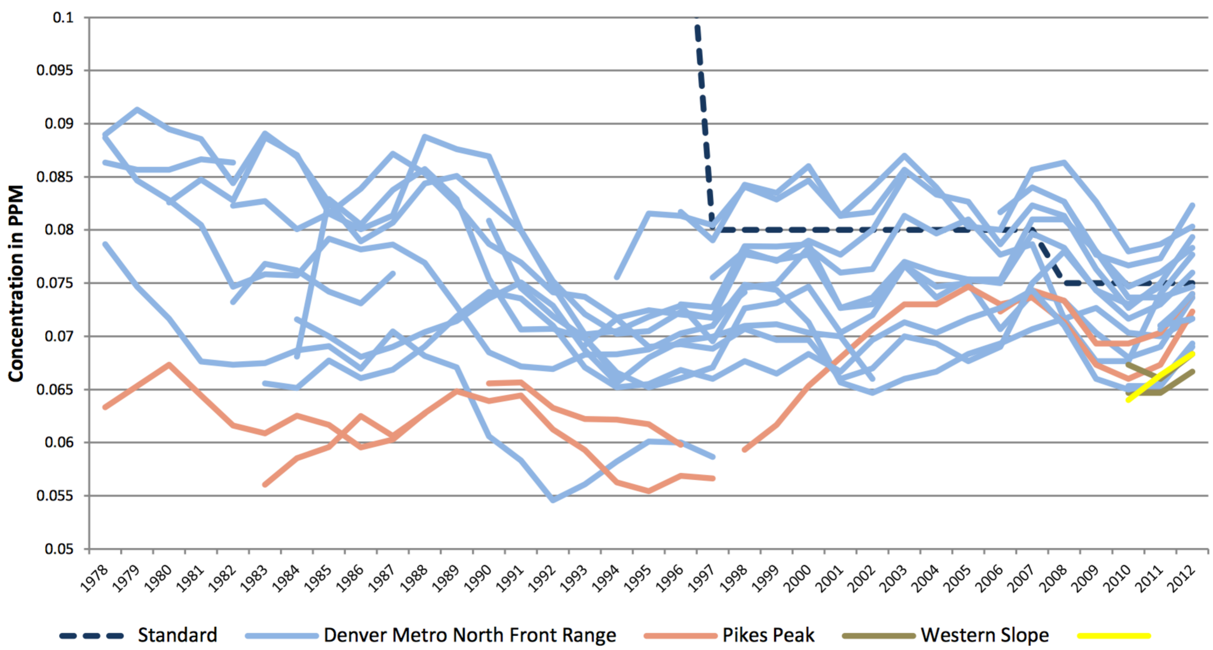
| | NOx | VOC | VOC percent |
|---|---|---|---|
| Vehicles: | 2,506 | 2,601 | 6.60 |
| Non-Road: | 601 | 659 | 1.67 |
| Wood burning: | 52 | 648 | 1.64 |
| Point Source: | 1,679 | 477 | 1.21 |
| Railroad: | 498 | 19 | 0.05 |
| Aircraft: | 23 | 33 | 0.08 |
| Forest/Ag. Fires: | 40 | 286 | 0.72 |
| Structure Fires: | 0 | 2 | 0.00 |
| Restaurants: | 0 | 37 | 0.09 |
| Biogenic: | 575 | 30,300 | 76.88 |
| Oil Gas Point: | 1,304 | 1,361 | 3.45 |
| Oil Gas Area: | 1,085 | 2,979 | 7.56 |
| Combustion: | 199 | 12 | 0.03 |
| Tank Trucks: | NA | 2 | 0.00 |
| Refueling: | NA | 166 | 0.42 |
| Portables: | NA | 80 | 0.20 |
| Pesticides: | NA | 138 | 0.35 |
| Solvents: | NA | 583 | 1.48 |
| Surface Coating: | NA | 417 | 1.06 |
| Total | 8560 | 39,413 | |

Source: 2010 Air Pollutant Emissions Inventory,
http://www.colorado.gov/airquality/inv_maps_2010.aspx, accessed December 28, 2013.

## Ozone levels in Colorado

Figure 1 displays a 34-year record of ozone concentrations in Colorado. Until 2008 the observations were reported only from locations in the Front Range. The values have been above the current EPA standard for much of that period. Data from the Western Slope were reported beginning in 2008 (note that this figure reports concentrations in parts per million but the next figure is in parts per *billion*).

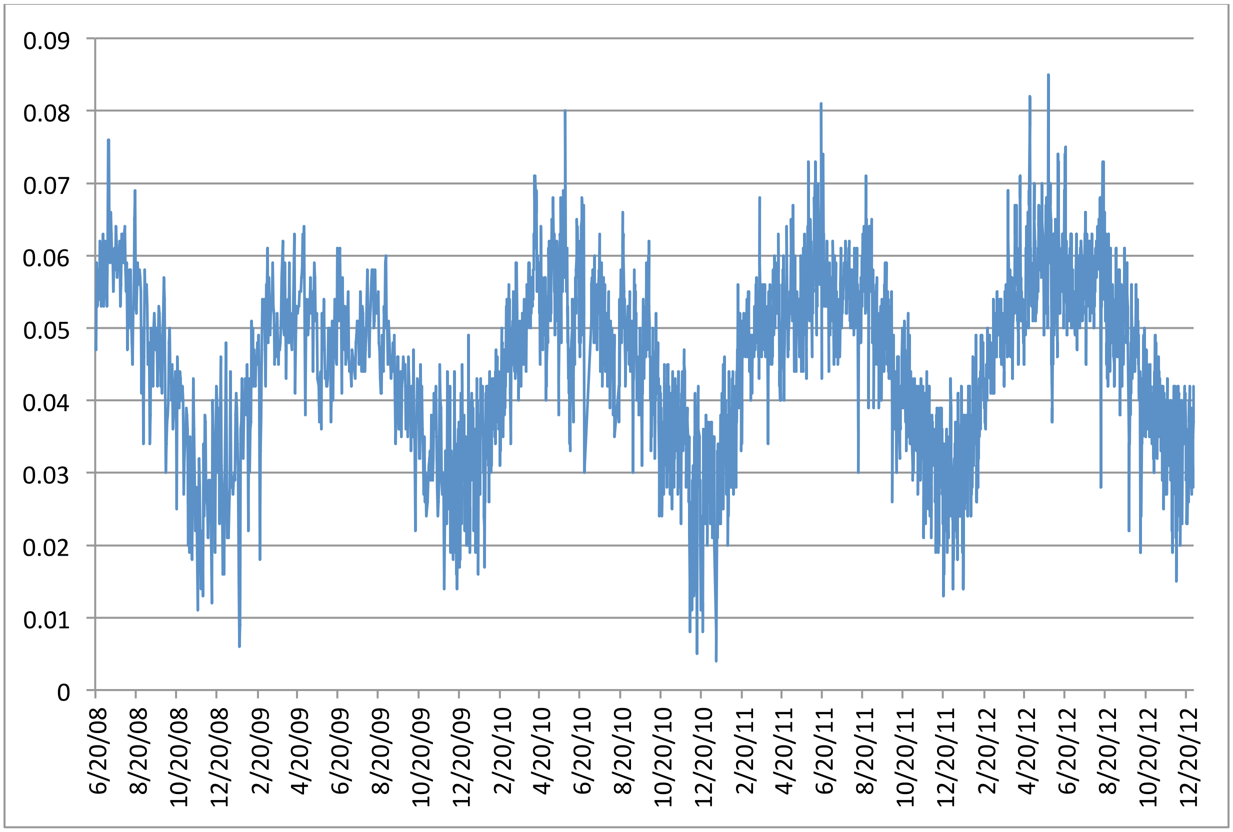
**Figure 1. Statewide Ambient Trends for Ozone (Parts per million)**




*Source: Figure 5 in Colorado Air Quality Data Report 2012, Colorado Department of Public Health and Environment, Air Pollution Control Division, November 2013.*

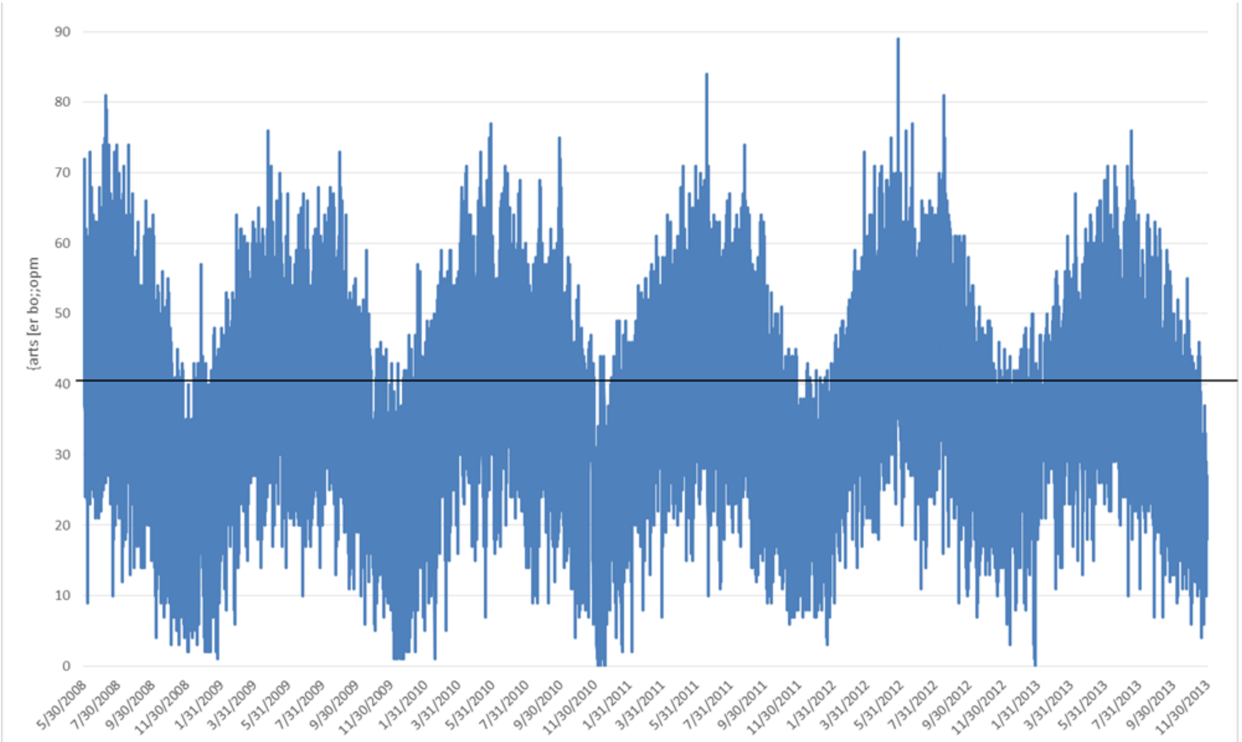
Figure 2 and Figure 3 report ozone trends in two locations in western Colorado – Rifle, west of Glenwood Springs and Palisade, located in the Grand Valley. Both locations have summertime highs as higher temperatures increase the rate of conversion of VOCs to ozone. In Rifle the peak values have been gradually increasing, from about .075 parts per million (75 parts per billion) to about 0.085 parts per million in 2012. As Figure 3 shows, summertime ozone levels in Palisade are in the 60 to 70 ppb range with spikes that go as high as 90 ppb.

**Figure 2. Rifle Daily Maximum Ozone Concentration June 2008 - December 2012 (parts per million)**



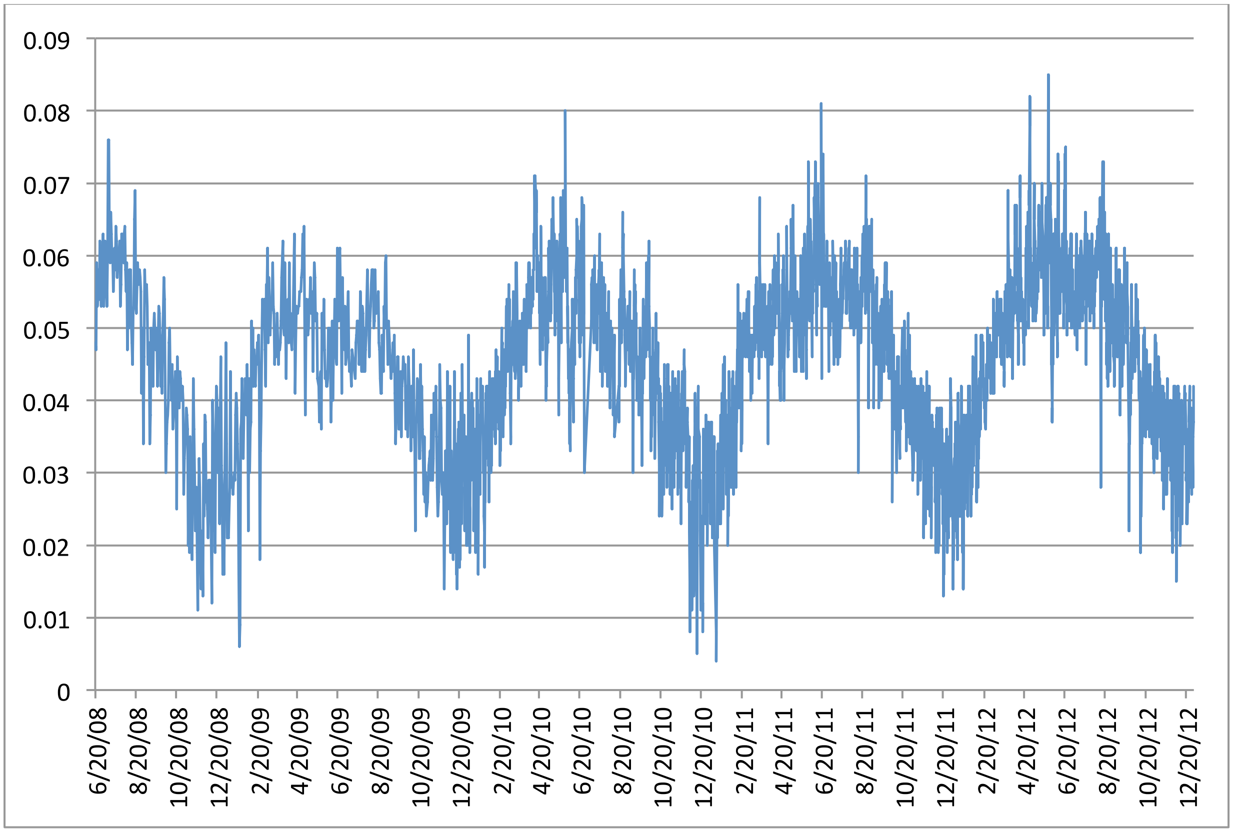

Source: Generated from data from the EPA Air Quality Statistics Report (http://www.epa.gov/airdata/ad_data.html, accessed December 29, 2013.

**Figure 3. Ozone Concentration, Palisade Water Treatment Plant, Hourly Observations, May 2008 to November 2013 (parts per billion).**




*Source: Generated from data provided by the Mesa County Air Quality Program.*

**Figure 4 Rifle Daily Maximum Ozone Concentration June 2008 - December 2012 (parts per million)**

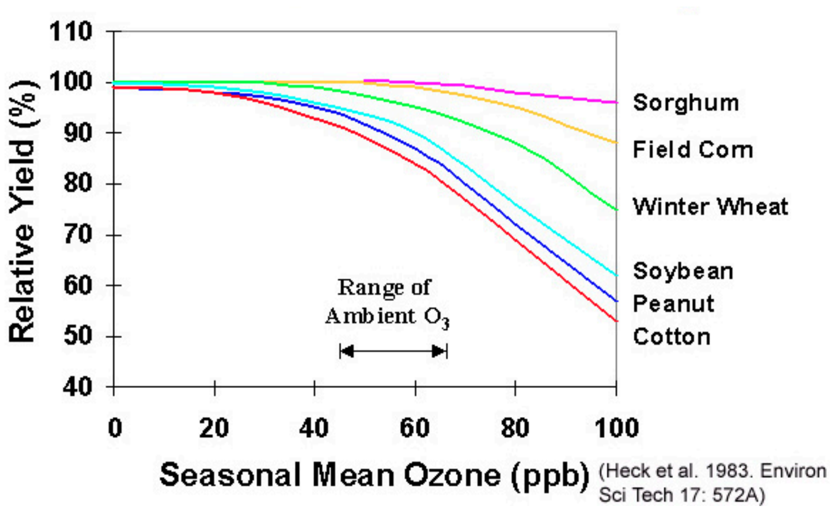



Source: Generated from data from the EPA Air Quality Statistics Report (http://www.epa.gov/airdata/ad_data.html, accessed December 29, 2013.

# Biological effects of ozone on plants[3]

The US Department of Agriculture reports "Ground-level (tropospheric) ozone causes more damage to plants than all other air pollutants combined." (http://www.ars.usda.gov/Main/docs.htm?docid=12462). Measurable economic damage to plants begins at background ozone concentration levels of 40 parts per billion (ppb); in other word at levels well below ambient concentrations in much of Colorado. Dicot species (most fruits and vegetables, including grapes and cherries) are more sensitive to yield loss caused by ozone than monocot species (many field crops). Figure 5 shows the effects of ozone on yields of important field crops in the US. For some crops (the dicot species soybeans, peanuts, and cotton) yield effects are observable at ozone concentrations of as little as 20 ppb. Field corn yields are not significantly affected until background ozone levels are above 70 ppb. For wheat, the effects become significant at ozone levels of 50 ppb. For all crops included in this figure, the effects are non-linear; as ozone concentrations increase, the effects become increasingly large.

**Figure 5. Effect of Ozone on Yield of Selected Crops**




Source: USDA based on Heck et al. (1983).

In a 2008 report, the British Royal Society (The Royal Society 2008) said

> "The impacts of $O_3$ on vegetation may lead to long-term effects on ecosystem structure and function and impacts on the carbon cycle. In addition to reductions in plant growth and photosynthesis, $O_3$ can reduce the yield and affect the nutritional quality of major crop species, including wheat, rice and soybean. Global yields of staple crops are reduced as a consequence of current $O_3$ exposure, and this impact is likely to increase in some regions even with the full implementation of current legislation. In the USA in the 1980s the annual cost of loss of arable crop production due to $O_3$ was estimated to be \$2–4 billion. In the EU in 2000 an estimated €6.7 billion was lost due to impacts to arable crops. For the same year global yield losses were estimated to be \$14–26 billion for rice, soybean, maize and wheat combined. In some rapidly developing regions such as South Asia the impact of $O_3$ on the production of some staple crops such as wheat and rice may present a significant threat to regional food security.

[3] This section draws heavily on http://www.ars.usda.gov/Main/docs.htm?docid=12462.

Research on the effects of ozone on orchard crops and vegetables is limited. In a recent study, Moretti et al. (2010) discuss the effects of ozone (and other greenhouse gases) on post-harvest quality of fruit and vegetable crops. They report

> "Greatest impacts [of elevated ozone] in fruit and vegetable crops may occur from changes in carbon transport. Underground storage organs (e.g., roots, tubers, bulbs) normally accumulate carbon in the form of starch and sugars, both of which are important quality parameters for both fresh and processed crops. If carbon transport to these structures is restricted, there is great potential to lower quality in such important crops as potatoes, sweet potatoes, carrots, onions and garlic.
>
> Exposure of other crops to elevated concentrations of atmospheric ozone can induce external and internal disorders, which can occur simultaneously or independently. These physiological disorders can lower the postharvest quality of fruit and vegetable crops destined for both fresh market and processing by causing such symptoms as yellowing (chlorosis) in leafy vegetables, alterations in starch and sugars contents of fruits and in underground organs. Decreased biomass production directly affects the size, appearance and other important visual quality parameters. Furthermore, impaired stomatal conductance due to ozone exposure can reduce root growth, affecting crops such as carrots, sweet potatoes and beet roots … ."

An extensive multiyear study in Austria of the effects of ozone on grapes found that juice quality is reduced and grape yield is smaller when ozone concentration levels are above 40 ppb with effects that carry into subsequent years (Soja et al. 2004).

# Biological effects of ozone on animals

Published research on the effects of ozone on livestock is limited. Presumably this is because the effects on are at least qualitatively similar to those in humans, with short-term damage to the lungs and less certain long-term consequences. Menzel (1984) reviewed the evidence to date about ozone toxicity in humans and animals.

> "Despite the existence of anatomical differences between human, subhuman primate, and dog lungs versus common experimental rodent lungs, the anatomical lesion of ozone inhalation occurs at the functionally equivalent site of the junction between the conducting airway and the respiratory region. Ciliated cells of the upper airways and the type 1 cell of the centriacinar region are most affected. Type 2 cell proliferation is a hallmark of ozone toxicity. A wide variety of biochemical and physiological changes have been noted in several animal species and in humans. … Ozone appears to be a weak mutagen and to produce chromosomal abnormalities. Defects in defense against airborne infection are present in animals, which are more susceptible to airborne infection after ozone exposure. … Despite the variety of toxic effects, few qualitative differences between species are apparent; rather, quantitative differences do occur."

# Preliminary estimates of the effects of ozone reduction on economically important agricultural activities in Colorado

According to the National Agricultural Statistics Service (National Agricultural Statistics Service 2012), agriculture contributed about $6.7 billion to the Colorado economy in 2010, the last year for which data are available. Of this total, $2.3 billion is from crops and $3.8 billion from animal agriculture. Important crops include corn ($604 million), wheat ($500 million in cash receipts, hay ($287 million), and vegetables ($358 million, of which $156 million are from potatoes). Note that statistics on fruit production are not available but presumably are included in the total value of agriculture.

We do not have enough data to estimate with any precision the effects of a decline in ozone concentrations on individual crops. But the agronomic information presented above suggests that Colorado agriculture experiences substantial yield declines as a result of current ozone levels with a 5 percent decline likely a conservative estimate.

To provide an initial indication of the economic benefits to Colorado's agriculture of ozone reduction, we assume a 5 percent *increase* in *yield* from a reduction in ozone translates into a 5 percent in production and no effect on producer prices. The results are reported in Table 3.

**Table 3. The value of a 5 percent increase in Colorado agricultural production (million 2010 dollars)**

| | 2010 value | 5 percent increase |
|---|---|---|
| Crops | 2,300 | 115 |
| corn | 604 | 30 |
| wheat | 500 | 25 |
| hay | 287 | 14 |
| vegetables | 358 | 18 |
| others | 551 | 28 |
| Livestock | 3,800 | 190 |
| | | |
| Crop and livestock | | 305 |

Source: National Agricultural Statistics Service (2012).

Based on the 2010 value of crops and livestock production, a 5 percent increase would be worth $305 million. Of this amount $190 million is from increased animal productivity and $115 million is from crops. Of the increased crop value, $30 million is from corn and $25 million from wheat. The large category of 'others', which presumably includes grapes and other fruits, has an increased value of $28 million.

# Conclusions

Agriculture is harmed by ozone. At current background levels of ozone in Colorado the damage is likely to be economically significant but the evidence is limited by insufficient recent agronomic research and lack of data collected on ozone levels in many of the important agricultural producing regions. Nonetheless a 5 percent decline in yield across seems likely to be a conservative estimate with some crops and animals experiencing greater losses. If this decline is in fact correct, the economic value of reducing ozone levels below the critical level is at least $305 million annually, with benefits slightly greater for livestock agriculture than crop agriculture. And within crops, corn and wheat would have benefits greater than $25 million each and a range of ‘other’ crops would see benefits of at least $28 million annually.

# References

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Moretti, C.L., L.M. Mattos, A.G. Calbo, and S.A. Sargent. 2010. “Climate Changes and Potential Impacts on Postharvest Quality of Fruit and Vegetable Crops: A Review.” *Food Research International* 43: 1824–1832. doi:10.1016/j.foodres.2009.10.013.

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Soja, G., T.G. Reichenauer, M. Eid, A.M. Soja, R. Schaber, and H. Gangl. 2004. “Long-Term Ozone Exposure and Ozone Uptake of Grapevines in Open-Top Chambers.” *Atmospheric Environment* 38 (15) (May): 2313–2321. doi:10.1016/j.atmosenv.2003.12.038.

The Royal Society. 2008. “Ground-Level Ozone in the 21$^{st}$ Century: Future Trends, Impacts and Policy Implications”. London: The Royal Society. royalsociety.org.

## Figure 6, Ozone Summary Table, 2013

****** DRAFT DATA ******

**2013 8-Hour Ozone (updated through September 30, 2013)**

| AQS Number | Site Name | 1st Max 8-Hour (ppm) | Date 1st Max 8-Hour | 2nd Max 8-Hour (ppm) | Date 2nd Max 8-Hour | 3rd Max 8-Hour (ppm) | Date 3rd Max 8-Hour | 4th Max 8-Hour (ppm) | Date 4th Max 8-Hour | 5th Max 8-Hour (ppm) | Date 5th Max 8-Hour |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **08-001-3001** | Welby | 0.082 | 07/17 | 0.082 | 08/29 | 0.077 | 07/18 | 0.077 | 08/17 | 0.076 | 07/11 |
| **08-005-0002** | Highland | 0.085 | 08/29 | 0.080 | 06/13 | 0.080 | 06/28 | 0.079 | 08/17 | 0.078 | 07/10 |
| **08-005-0006** | Aurora East | 0.081 | 08/29 | 0.078 | 07/18 | 0.074 | 08/17 | 0.073 | 05/31 | 0.073 | 07/12 |
| **08-013-0011** | S. Boulder Creek | 0.086 | 07/17 | 0.081 | 07/10 | 0.080 | 07/11 | 0.079 | 07/16 | 0.075 | 07/22 |
| **08-031-0002** | CAMP | 0.074 | 07/10 | 0.072 | 07/17 | 0.069 | 08/29 | 0.067 | 07/11 | 0.064 | 08/04 |
| **08-031-0026** | La Casa | 0.080 | 07/10 | 0.079 | 07/17 | 0.072 | 07/11 | 0.071 | 08/29 | 0.070 | 06/28 |
| **08-035-0004** | Chatfield State Park | 0.086 | 08/29 | 0.085 | 06/28 | 0.083 | 07/18 | 0.083 | 07/21 | 0.082 | 08/17 |
| **08-041-0013** | Colo. Spgs. – USAF Academy | 0.082 | 07/18 | 0.079 | 05/31 | 0.075 | 07/12 | 0.074 | 06/09 | 0.074 | 07/20 |
| **08-041-0016** | Manitou Springs | 0.078 | 07/18 | 0.077 | 08/29 | 0.075 | 05/31 | 0.072 | 08/17 | 0.071 | 07/12 |
| **08-045-0012** | Rifle – Health | 0.065 | 05/31 | 0.064 | 05/23 | 0.064 | 07/10 | 0.062 | 06/05 | 0.062 | 06/21 |
| **08-059-0005** | Welch | 0.084 | 07/17 | 0.080 | 07/21 | 0.080 | 08/17 | 0.080 | 08/29 | 0.077 | 08/16 |
| **08-059-0006** | Rocky Flats - N | 0.093 | 07/17 | 0.087 | 07/10 | 0.086 | 08/17 | 0.085 | 07/11 | 0.081 | 06/09 |
| **08-059-0011** | NREL | 0.090 | 07/17 | 0.086 | 07/11 | 0.084 | 08/17 | 0.084 | 08/29 | 0.082 | 07/10 |
| **08-059-0013** | Aspen Park | 0.080 | 08/29 | 0.078 | 06/12 | 0.078 | 07/17 | 0.077 | 07/18 | 0.077 | 08/17 |
| **08-069-0007** | NPS - Rocky Mtn. NP | 0.082 | 06/12 | 0.082 | 07/17 | 0.079 | 07/16 | 0.074 | 06/20 | 0.074 | 07/17 |
| **08-069-0011** | Ft. Collins - West | 0.091 | 07/17 | 0.087 | 08/17 | 0.085 | 07/11 | 0.082 | 07/10 | 0.080 | 07/03 |
| **08-069-0012** | * Rist Canyon | 0.070 | 06/12 | 0.068 | 05/25 | 0.067 | 05/17 | 0.066 | 06/02 | 0.066 | 06/09 |
| **08-069-1004** | Ft. Collins - CSU | 0.083 | 07/17 | 0.076 | 08/17 | 0.075 | 07/11 | 0.074 | 07/10 | 0.071 | 07/03 |
| **08-077-0020** | Palisade - Water | 0.068 | 07/18 | 0.067 | 07/10 | 0.066 | 06/01 | 0.066 | 07/17 | 0.065 | 05/23 |
| **08-081-0002** | Lay Peak | 0.067 | 07/10 | 0.066 | 07/19 | 0.066 | 08/16 | 0.065 | 06/11 | 0.065 | 07/09 |
| **08-083-0006** | Cortez | 0.065 | 05/31 | 0.064 | 07/10 | 0.064 | 07/17 | 0.064 | 07/18 | 0.062 | 05/05 |
| **08-123-0009** | Greeley - Weld Tower | 0.080 | 08/17 | 0.074 | 07/11 | 0.074 | 08/16 | 0.073 | 06/18 | 0.073 | 09/07 |

**NOTE:** Values above the level of the 8-hour standard (0.075 ppm) are highlighted in yellow.
**NOTE:** Data influenced by natural event values, if any, are included.
* Rist Canyon site shut down on 6/28/2013.

*Colorado Department of Public Health and Environment, Air Pollution Control Division, Technical Services Program*

Source: http://www.colorado.gov/airquality/html_resources/ozone_summary_table.pdf, Accessed December 28, 2013