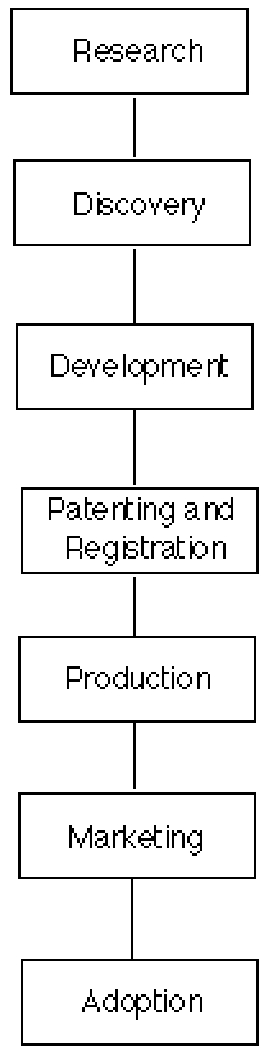
Technological Change and Pollution Control

In many situations, especially when aggregate behavior is analyzed, it is useful to model technological opportunities by continuous well-behaved production functions such as $Y = AK^{\alpha} L^{\beta}$ (Y = output, K = capital, L = labor). A more detailed analysis of production systems recognizes that they consist of distinct technologies that may be embodied in specific capital goods (or may be associated with distinct management strategies). In the short run, production coefficients (input-output relationships) may not differ very much. A significant change in production coefficients may require adoption of a new technology.

For example, one can distinguish between "gas guzzlers" and fuel-efficient cars and between mechanical (combine) and manual (sickle) harvesting.

New technologies provide an important avenue to address environmental problems. Policy designs have emphasized solutions that lead to both adoption and innovation of new technologies.

The Life Cycle of the Technology



Innovations—new tasks to perform, new products, and new procedures—are elements of both technological and institutional change. Technological changes are innovations leading to changes in production technology, and institutional innovations are new organizational structures. Innovations in most cases are results of discoveries. Historically, practitioners made most discoveries, but in our century they increasingly become the results of research efforts.

It is useful to distinguish between "basic" and "applied" research. Basic research aims to understand basic principles and applied research to discover and develop technologies. University researchers are more likely to concentrate on "basic" research, while industry research has a more applied emphasis.

Some of the more important innovations that originated in university research were patented by university scientists and then refined by the industry. A process of "technology transfer" is responsible for commercialization of university research.

Scientists have to make choices about their research direction, and their choices affect the nature of the resulting technology and innovation. The “Induced Innovation Hypothesis” argues that the nature of innovation and new technology reflects economic condition or invention as an economic activity.

Americans developed the steel plow and tractor because the country had a labor scarcity, and technologies that save land have been of special value. Increase in energy prices lead to development of fuel-efficient cars and electric appliances. The United States began supporting yield-increasing research in agriculture at the end of the 19^{th} century when most of the land base in the United States was settled.

One byproduct of environmental regulation is investment in research aimed to reduce pollution. Concerns about the environmental side effects of pesticides propelled companies to invest in biotechnology and other technologies to replace harmful chemicals. Once substitutes are available, polluting-generating activities are more strictly regulated. The energy crises of the 1970s led to the development of alternative energy industries and research on solar power and energy-saving devices. Investment in such research declined as energy prices declined. With concerns about global warming, there is much more investment and interest in such research.

Investment in research is a key element of environmental policies.

(1) Research enables discovery of basic environmental problems. Without research, not much would have been known about the link between smoking and cancer.

(2) Research provides better monitoring and management equipment to help identify environmental problems and monitor response.

(3) Public research enables sustaining development of technologies that may not be economical under existing prices.

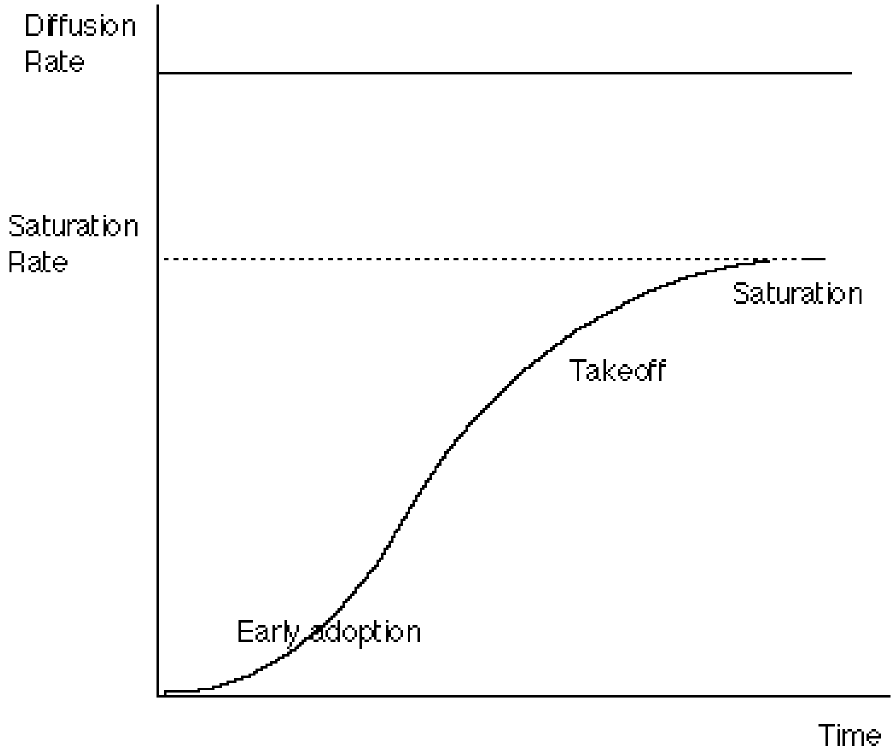
Adoption of Innovations

There is a significant time lag between the time a new innovation is introduced and the time it is widely used by producers or consumers.

Diffusion is the aggregate process of product penetration. It is measured by the percentage of potential users that actually adopt a technology.

Adoption is a decision by a specific individual to use a technology. Diffusion is aggregate adoption.

Diffusion curves measure aggregate adoption as a function of time. They tend to be S-shaped.



There are two theories that explain the S-shape of diffusion curves. One explanation is that diffusion is driven by imitation. It takes time for a critical number of individuals to adopt the technology before it is adopted by a large mass of people during a short period of time (takeoff period).

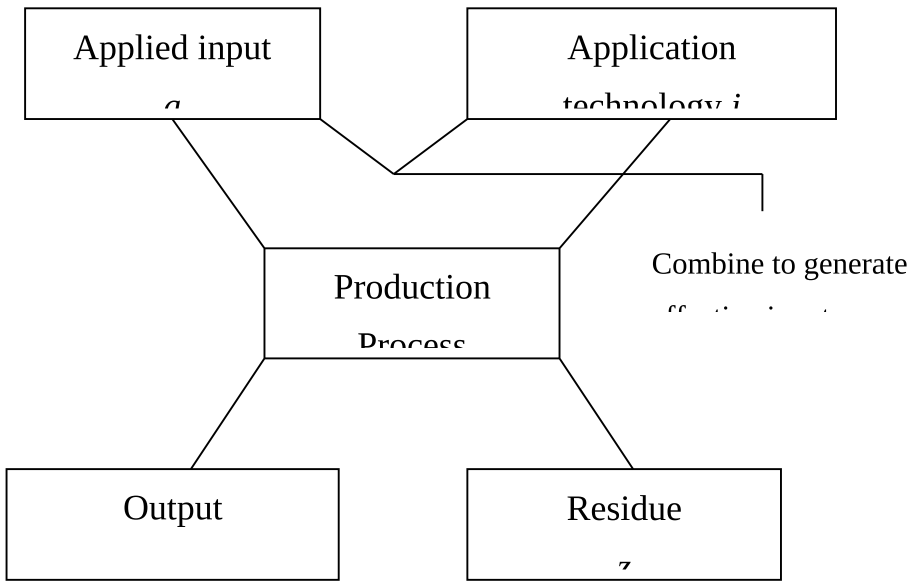
An alternative explanation for the S-shaped diffusion curve is heterogeneity between users and declining prices of new technology because of learning-by-doing (manufacturers can produce it cheaper). First, the larger, richer users adopt a new technology and, when it becomes cheaper, the others follow suit.

The profitability of the technology relative to existing ones is a driving force in the diffusion process. Diffusion takes off as the technology becomes more profitable.

Diffusion of cleaner technology is accelerated by incentives that make traditional technologies less profitable. Integrated pest management is more likely to be diffused widely if pesticides are more strictly regulated. Alternatively, subsidies of cleaner technologies are likely to accelerate their adoption.

Adoption Choices of Conservation Technology

Some production processes may not consume applied input completely, and the residue is a source of pollution problems. For example, when fertilizers are applied on a field, a certain percentage is utilized, and the excess ends up as a runoff or may infiltrate to contaminate ground water.



It is useful to present the production function as $y = f(e)$ when e is effective input. Effective input is determined according to

$$e = h(i,\alpha)\ a$$

where

a = applied input
i = application technology

and

α = an indicator of environmental condition $0 \le \alpha \le 1$.

The variable i can assume only discrete values. Let $i = 0$ for the traditional technology and $i = 1, 2, 3\ldots$ for the modern technologies. The variable α is an indicator of environmental parameters that affect input use application.

For example, water can be irrigated through traditional gravitational technology (furrows or flood systems) or with sprinkler or drip irrigation. Some of the applied water will end up as runoff or deep percolating ground water. Irrigation efficiency depends on water-holding capacity and slope of the land. If land capacity is poor, much of the crop will not retain water that is applied with traditional technology. The same happens when the land has a steep slope. $h_i(\alpha)$ is input use efficiency, the percentage of the input applied which is actually consumed by the crop.

For convenience, let $\alpha = h_0(\alpha)$. The indicator of environmental quality is equal to input use efficiency under traditional technology. In the case of irrigation, $\alpha = .6$ implies that the crop utilizes 60 percent of the applied water at a specific location when applied with traditional technology.

Transition to modern technology tends to increase input use efficiency. In the case of sprinkler irrigation, input use efficiency for land of $\alpha = .6$ is .85 and $h_1(.6) = .85$. Namely, the crop utilizes 85 percent of the applied water.

Under drip irrigation $(i = 2)$, water use efficiency for land with $\alpha = .6$ is .95; thus, $h_2(.6) = .95$.

The unused residue is a source of pollution. Let this residue be denoted by *Z*, then

$$Z = [1 - h_i(\alpha)]a.$$

For convenience, let Z_i and a_i denote residue and input use respectively, with technology *i*. Under traditional technology, when $\alpha = .6$, $Z_0 = .4a_0$. Switching to sprinkler irrigation results in $Z_1 = .15a_2$, and adoption of drip irrigation $(i = 2)$ reduces residues significantly—$Z_2 = .95a_2$.

When pesticides are applied aerially, $(i = 0)$, input use efficiency may be .25 $(\alpha = .25)$, but transition to a modern precision application may increase input use efficiency to .95 $h_1(.25) = .95$. Thus, the adoption of the more precise technology reduces residue from $Z_0 = .75a_0$ to $Z_1 = .05a_1$.

Technologies that increase input use precision are not restricted to agriculture. Increased efficiency of fuels in cooking and heating equipment both conserve fuels and reduce negative side effects associated with the evaporation of unconsumed fuels. (Unburned cooking fuels are presumed to be a major component of the air pollution problem in Mexico City.) Similarly, some forests may be clear-cut only to utilize a small percentage of the trees which have commercial value. Precise harvesting, which pinpoints only the appropriate trees, will reduce environmental damage. Similarly, a major environmental problem in fishery management is by-catch. Using nets, fishermen catch all the fish above a certain size, but keep only a fraction of these fish—the ones with commercial value. The others are destroyed. Much of the damage to fisheries can be avoided by adoption of more precise fishing technologies.

Adoption of resource-conserving technologies that tend to reduce residues is hampered by the higher fixed costs these technologies require relative to traditional technology. Returning to our model, let k_i denote the fixed annual cost of using technology *i* by t_k production units. We will assume that $k_1 > k_0$, and hence modern technologies have higher fixed costs than traditional ones.

In many circumstances, the decision whether or not to adopt a technology is a dynamic one. Here we will simplify and deal with static choices, made annually.

First, we will consider choices when pollution costs are ignored. We will assume that the technology is divisible. A firm has a capacity constraint, and k_i is fixed cost per unit of capacity, but this capacity can be divided. Let δ_i be the share of the productive capacity used with technology *i*. We know that $0 \le \delta_i \le 1 \quad 0 \le \delta_0 + \delta_i \le 1$. The producer has to decide to what extent to use the modern technology and input use under each technology. The producer optimization problem is:

$$\max_{a_0, a_1, \delta_0, \delta_1} \delta_1 \left[pf\left(a_1 h_1(\alpha)\right) - w_1 a_1 - k_1 \right] + \delta_0 \left[pf\left(a_0 \alpha\right) - w_0 a_0 - k_0 \right]$$

$$\text{subject to} \quad 0 \le \delta_1 + \delta_0 \le 1$$
$$0 \le \delta_1, \delta_0 \le 1$$

This optimization problem can be solved in 2 steps:

(i) Choice of optimal input use for each technology

$$\prod_i = \max_{a_i} pf(a_i h_i) - w_i a_i - k_1$$

The first order conditions that hold at the optimal level of a_i are:

$$p\frac{\partial f}{\partial e}(e_i)h_i(\alpha) - w_i = 0$$

↑ value of marginal product of <u>applied</u> input

↑ price of applied input *i*

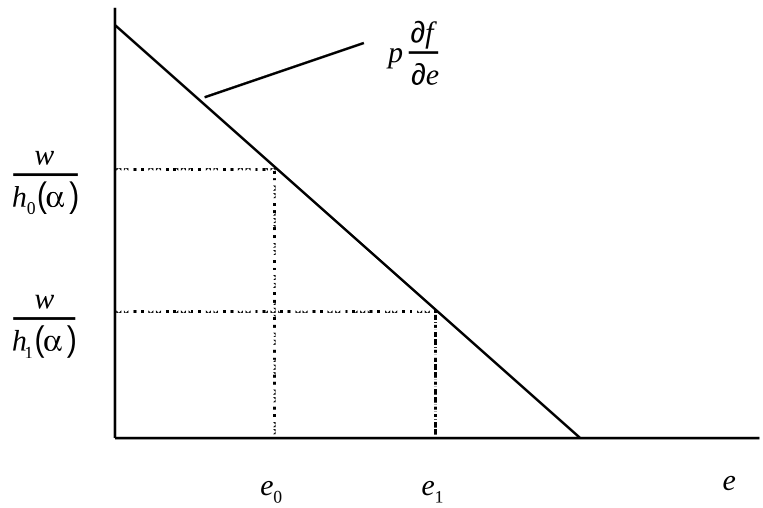
By rearranging terms, this condition can be rewritten

$$p\frac{\partial f}{\partial e}(e_i) = \frac{w_i}{h_i(\alpha)}$$

↑ value of marginal product of <u>effective</u> input

↑ price of effective input

The last condition enables comparison of optimal outcomes under technologies 0 and 1.



Since $h_0(\alpha) < h_1(\alpha)$, the price of effective input under technology 1 is greater than under technology 0. Thus, $e_1 > e_0$ and, hence, $y_1 > y_0$. More output will be produced with the modern technology.

The relationship between a_1 and a_0 is not straightforward.

$a_1 = e_1 / h_i(\alpha)$ and $a_0 = e_0 / \alpha$

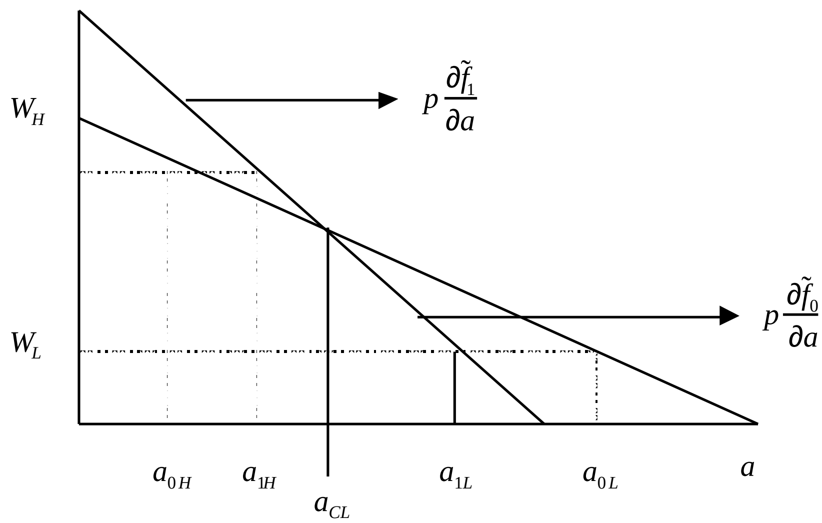
$a_1 \gtrless a_0$ if $\frac{e_1}{e_0} > \frac{h_i(\alpha)}{\alpha}$

so if the <u>proportional</u> increase in effective input from adoption is greater than the increase in input use efficiency, adoption of the modern technology will lead to increased input use. If $e_1 / e_0 < h_i(\alpha)/\alpha$, less input will be used with the modern technology. The greater the e_1 / e_0 ratio, the larger is the output-increasing effect of adoption. Adoption will lead to increased applied input use if that will lead to very significant output effect. If output effect is small, and e_1 is not much larger than e_0, adoption may lead to input savings.

We can rewrite the production function as

$y = \tilde{f}_i(a_i) = f(a_i h_i(\alpha))$. The marginal productivity of *a* under technology *i* is

$$\frac{\partial \tilde{f}_i}{\partial a_i}(a_i) = \frac{\partial f}{\partial e}(e_i) h_i(\alpha)$$



The value of the marginal product of applied input under the modern technology $\left[p \frac{\partial \tilde{f}_1}{\partial a_1}(a_1) \right]$ is greater than the value of the marginal product of the applied input under the traditional technology $\left[p \frac{\partial \tilde{f}_0}{\partial a_0}(a_0) \right]$ below non-critical level a_{CL}. If the price of applied water is high, so that both a_1 and $a_0 < a_{CL}$, $a_1 > a_0$. But if *W* is sufficiently low, and both a_1 and a_0 are greater than a_{CL}, $a_0 > a_1$ and adoption of the modern technology will save input.

To analyze the adoption decision, let

$$\Pi_1 = pf\left(a_1 h_1(\alpha)\right) - wa_1 - k_1$$
$$\Pi_0 = pf\left(a_0(\alpha)\right) - wa_0 - k_0$$

If $\Pi_1 > \Pi_0$, modern technology is adopted.
If $\Pi_0 > \Pi_1$, modern technology is not adopted.

Let $y_1^* - y_0^* = \Delta y$ output increase
$a_0^* - a_1^* = \Delta a$ input saving

Adoption of modern technology will increase output $(\Delta y > 0)$ and in most reasonable cases save input $(\Delta a < 0)$.

If $p\Delta y + W\Delta a > k_1 - k_0$ the modern technology is adopted.

Adoption is likely to

(1) Increase output price
(2) Increase input price
(3) Cause fixed cost of modern technology to decline

<u>Pollution Tax Considerations</u>

Now, consider the case with pollution tax V_1. The profit under technology *i* becomes

$$\prod_i = \max_{a_i} pf\left(h_i(\alpha)a_i\right) - w_i a_i - Va_i\left[1 - h_i(\alpha)\right] - k_1$$

↑ revenue ↑ input cost ↑ pollution cost ↑ fixed cost

The optimality condition condition for choice of a_i is

$$p\frac{\partial f}{\partial e}\left(e_i\right)h_i(\alpha) - w_i - V\left[1 - h_i(\alpha)\right] = 0$$

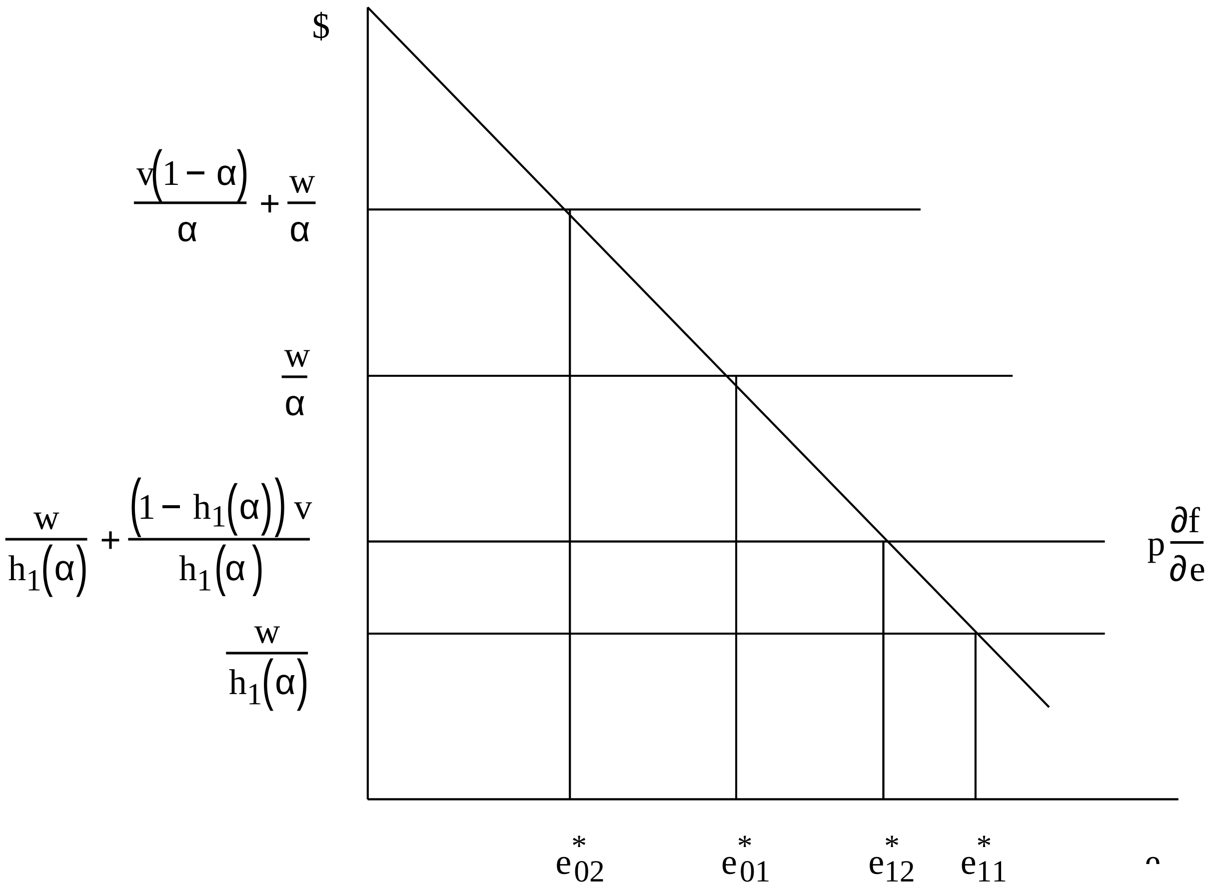
where $V\left[1 - h_i(\alpha)\right]$ is the cost of marginal pollution of input. This cost increases as input use efficiency $\left(h_i(\alpha)\right)$ declines. Optimal a_1^* is determined when the value of the marginal product of input is equal to the sum of its price (W) and the cost of the marginal pollution of applied input. Alternatively, the optimality condition can be presented as

$$p\frac{\partial f}{\partial e}\left(e_i\right) = -\frac{W}{h_i(\alpha)} + \frac{V\left[1 - h_i(\alpha)\right]}{h_i(\alpha)}$$

value of marginal product of — price of effec- — cost of marginal pollution of effective

effective input tive input input

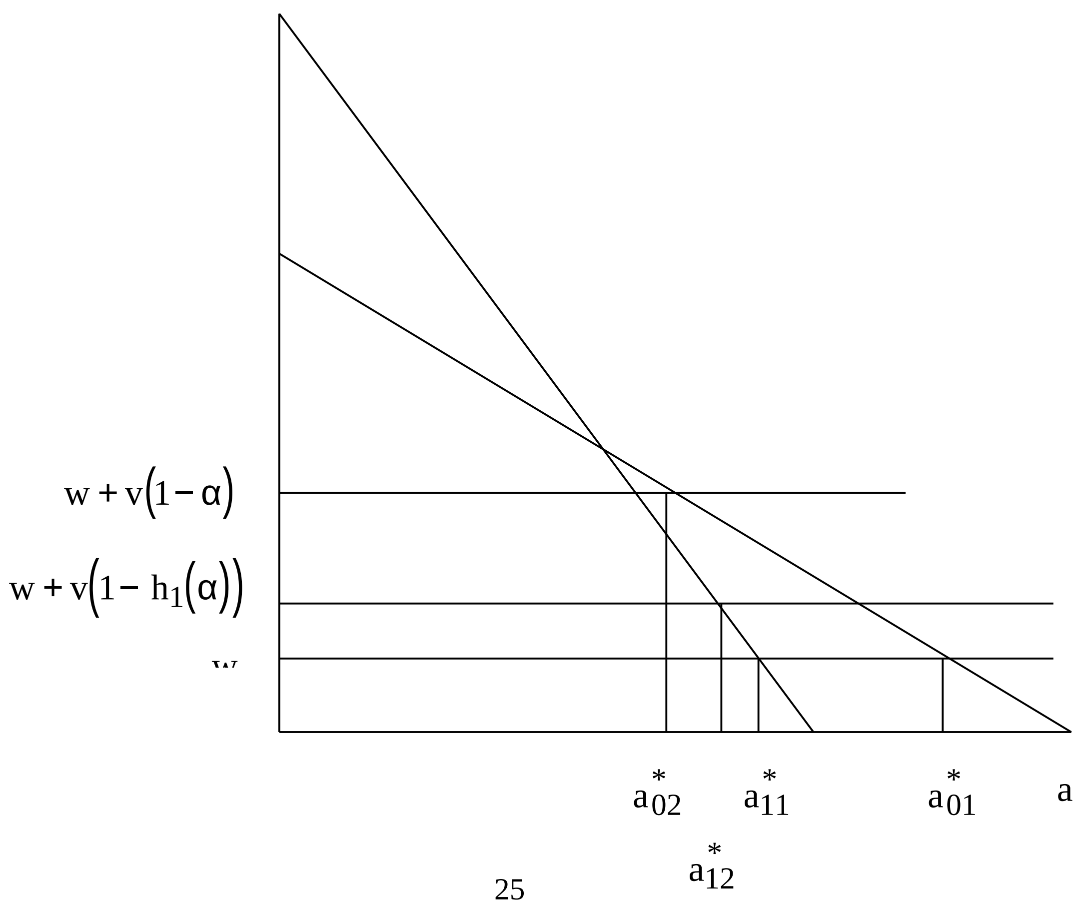
The introduction of a pollution tax will reduce the gap between the marginal cost of effective input tax under the traditional and modern techniques. The tax will increase the marginal cost of effective input under the traditional technology by $V(1-\alpha)/\alpha$. For $\alpha = .6$, the increase will be equal to $2V/3$. If $h_1(.6) = .85$ (moving, say, from furrow to drip irrigation), the marginal cost of the modern technology will increase by $\frac{.05V}{.95} = V/19$. Thus, the tax will be likely to increase the $e_1^* - e_0^*$, and hence $y_1^* - y_0^*$. This is depicted in the figure below.



$
$\frac{v(1-\alpha)}{\alpha}+\frac{w}{\alpha}$
$\frac{w}{\alpha}$
$\frac{w}{h_1(\alpha)}+\frac{(1-h_1(\alpha))v}{h_1(\alpha)}$
$\frac{w}{h_1(\alpha)}$
$p\frac{\partial f}{\partial e}$
e^*_{02}
e^*_{01}
e^*_{12}
e^*_{11}

The optimal effective input under technology *i* under tax is e_{i2}^* and without tax e_{i1}^*. The figure demonstrates how the tax is likely to increase the gap in effective input under the two technologies.

To assess the impact of the tax on actual input use, note that the tax leads to a lower marginal pollution cost under the modern technology, since this marginal cost is $V(1-h_i(\alpha))$. As the figure below shows, the marginal cost of applied input will become significantly higher under the traditional technology so that the introduction of a pollution tax is likely to reduce input use under the traditional technology more than under the modern one $\left(a_{01}^* - a_{22}^* > a_{11}^* - a_{12}^*\right)$. Furthermore, the pollution tax may cause less input use under the traditional technology than the modern technology, $\left(a_{12}^* > a_{02}^*\right)$, even though $\left(a_{01}^* > a_{11}^*\right)$.


$w + v(1 - \alpha)$
$w + v(1 - h_1(\alpha))$
a_{02}^*
a_{11}^*
a_{01}^*
a
a_{12}^*

Taxation of drainage, pesticide residue, and other types of pollution is likely to lead to adoption of modern technologies because taxation impact on the profit of traditional technology is larger. But such taxation may also lead to exits from the industry, since after-tax operation under both technologies is not profitable.

One way to counter the tax's negative effect on profitability is to use the tax measures to subsidize adoption of the modern technology. A firm may adopt if

(1) $$py_1^* - wa_1^* - v[1 - h_1(\alpha)]a_1^* - k_1 > py_0^* - wa_0^* - v(1-\alpha)a_0^* - k_0$$

and if

(2) $$py_1^* - wa_1 - v[1 - h_1(\alpha)]a_1^* - k_1 > 0.$$

A subsidy that will reduce k_1 will improve the likelihood that both conditions (1) and (2) will hold.

In many cases the residue is not observable, but optimal allocation can be obtained if water use is taxed according to technology choice. Water taxed under technology *i* is $v[1-h_i(\alpha)]$, and thus the water tax for drip irrigation will be smaller than under furrow irrigation. Similarly, taxes for adopters of precision chemical applications will be smaller than for those who use aerial spray.

It may be difficult to distinguish between input used with varied technologies, so in some cases a second-best policy of uniform input tax (a sales tax) is introduced. Sometimes it is accompanied by a technology tax or subsidy. For example, sewer fees are added to water bills even though sewage generation varies by individual. Energy prices may include a pollution fee, and can be accompanied by conservation subsidies.