increased, thus increasing the computing power per chip. Because the basic cost of manufacturing the microchip has not dramatically increased over these four decades, the cost per functional unit, and the cost of computing power, has gone down exponentially. It is this economic argument, the cost of silicon real estate, that drives Moore's Law.

For the past decade, however, the size of the microchip has remained roughly constant, so that factors (i) and (iii) have become more important. Today, as pointed out above, we are approaching the atomic limit on critical size. We are left, therefore, with the conclusion that it is factor (iii) that will have to provide the continuity to Moore's Law. What does this say about the role of nanowires?

Although transistors have very short gate lengths (the critical dimensions mentioned above), they have much larger widths in order to provide the current necessary to make the circuits work. If we are to replace the current planar transistor with nanowires, we will have to use a great many such devices in parallel to provide this current. But, we must satisfy the above economic driving forces, and effectively use the overall silicon real estate. This leads to a geometric argument that says that nanowires in the plane will not effectively compete with novel transistors such as the "fin" field effect transistor, or "finFET," Basically, the finFET is a vertically oriented Si "fin" in which transistor structures can be placed on both sides (*8*, *9*), and even on the top (*10*), of this fin. A properly configured finFET more effectively uses silicon real estate. Consequently, there does not seem to be much of a role for nanowires laid horizontally on the Si surface (*11, 12*). However, nanowires can be grown vertically, and this growth can be initiated on a wide variety of substrates (*4*).

As mentioned, currently the transistors are placed in a planar array, but they are overlaid with a great many metal lines, with nine or more levels of metal (worse than any freeway interchange). These metal lines provide power, clock signals to synchronize the switching of the transistors, and various interconnections between the different functional blocks of the chip. Connections from these metal lines to the transistors are made by downwardly reaching metal fingers called "vias." When we can no longer reduce the transistor size, we enhance the use of Si real estate by moving vertically.

Our third Moore's Law factor—cleverness—can be increased by replacing some of these vias with vertical nanowire transistors (*13*) (see the figure). These vertical transistors can reach from the silicon to a metal wire or even between different levels of metal wire. Moreover, we can begin to think about creating reconfigurable architectures in which the connections between different functional blocks are changed by switching just a few of these vertical transistors. Thus, we begin to create real three-dimensional architectures in a different manner from the traditional approach of stacking chips (*14*).

If we are to use these vertical transistors for more effective architectures, then we have to change how we go about microchip design. Today, this chip design is done with automated transistor layout programs that optimize the planar design placing of the various functional blocks and minimize the necessary interconnections (in the metal layers). To change to reconfigurable architectures, we need switchable interconnections based on vertical transistors, and device physicists will have to work with circuit designers to achieve this. These new opportunities for nanowires to extend Moore's Law may well force this paradigm shift.

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CLIMATE

Food Security Under Climate Change

Food insecurity is likely to increase under climate change, unless early warning systems and development programs are used more effectively.

Molly E. Brown and Christopher C. Funk

Some of the most profound and direct impacts of climate change over the next few decades will be on agricultural and food systems. On page 607 of this issue, Lobell *et al.* (*1*) show that increasing temperatures and declining precipitation over semiarid regions are likely to reduce yields for corn, wheat, rice, and other primary crops in the next two decades. These changes could have a substantial impact on global food security.

Since the 1990s, rising commodity prices and declining per capita cultivated area have led to decreases in food production, eroding food security in many communities (*2*). Many regions that lack food security rely on local agricultural production to meet their food needs. Primarily tropical and subtropical, these regions are substantially affected by both global climate variations and global commodity price fluctuations. Warming in the Indian Ocean (*3*) and an increasingly "El Nino–like" climate (*4*) could reduce main-season precipitation across parts of the Americas, Africa, and Asia (see the figure).

In food-insecure regions, many farmers both consume their product and sell it in local markets. This exposes farmers to climate variations, because when they produce less their income goes down while their costs go up to maintain basic consumption. Large-scale hunger can ensue, even when there is sufficient food in the market that has been imported from elsewhere.

National revenue can also be affected by large-scale droughts, which restrict the ability of countries with small budgets to purchase grain on the international market. Thus, recent large increases in grain prices reduce access to food for the poor, for example, in Tanzania, who compete for corn with ethanol producers and hog farmers in the United States. Finally, up to half of all malnutrition is driven by nonfood factors through diseases such as HIV/AIDS and malaria; the latter disease is

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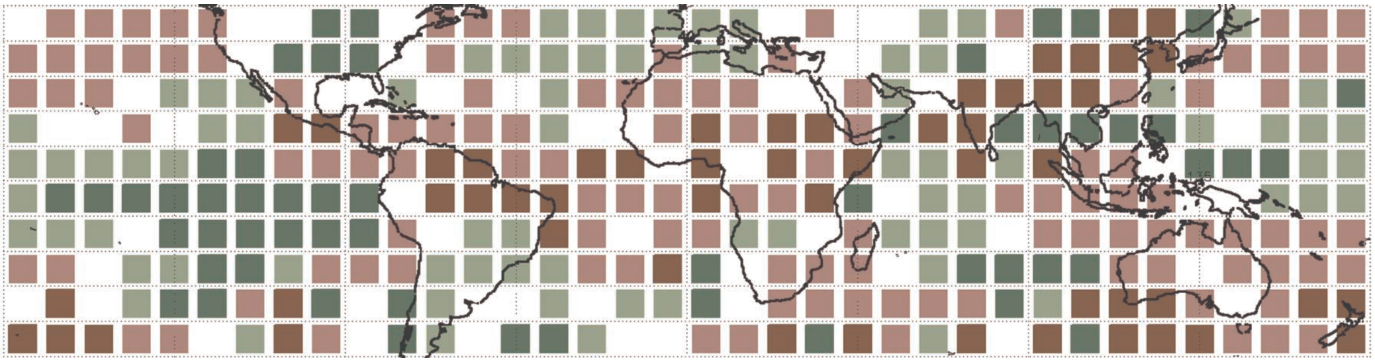

Upcoming change. Each 10° grid cell in this map shows the anticipated impact of warming in the Indian (*3*) and eastern Pacific (*4*) Oceans, expressed as a shift in standardized precipitation, ΔP, in the dominant 3-month season (*8*). σ is the standard deviation. Several regions where precipitation is likely to change over the next 50 years—such as eastern and southern Africa—already face significant food security problems.

likely to become more severe and widespread with warming temperatures.

Lobell *et al.* use crop models to calculate changes in agricultural production to 2030. The results show that climate change is likely to reduce agricultural production, thus reducing food availability. Identifying the impact of this reduced production will, however, be complicated by other changes. The latter include rising oil prices, the globalization of the grain market, and a structural change in demand for key food supplies due to increasing demand for biofuels and rising per-capita consumption in India and China. These changes have pushed up supply costs for staple foods by 40% or more in many food-insecure areas. Decoupling these effects to implement mitigation and adaptation programs will be difficult.

Climate change impacts on farmers will vary by region, depending on their use of technology. Technological sophistication determines a farm's productivity far more than its climatic and agricultural endowments. Food insecurity, therefore, is not solely a product of "climatic determinism" and can be addressed by improvements in economic, political, and agricultural policies at local and global scales. In currently food-insecure regions, farming is typically conducted manually, using a hoe and planting stick with few inputs. The difference between the productivity of these farms and those using petroleum-based fertilizer and pesticides, biotechnology-enhanced plant varieties, and mechanization is extreme (*5*). Not only will climate change have a differential effect on ecosystems in the tropics due to their already warmer climates, but also poor farmers in the tropics will be less able to cope with changes in climate because they have far fewer options in their agricultural system to begin with. These handicaps can be exacerbated by macro-economic policies that create disincentives for agricultural development, such as agricultural subsidies in the United States and Europe and poorly implemented cash transfer programs (*6*).

The study by Lobell *et al.* suggests that communities can cope with climate change, for example, by switching from producing corn to producing sorghum, whose lower water requirements and higher temperature tolerances are better suited to a warmer and drier climate. However, this adaptation measure may be impossible to implement in many parts of the developing world. For example, it assumes markets for millet in regions where only maize is eaten, and technology and know-how about how to process and consume sorghum in maize zones. Communities may nevertheless be forced, as they are today, to consume what they produce regardless of cultural preferences.

Today, millions of hungry people subsist on what they produce. If climate change reduced production while populations increase, there is likely to be more hunger. However, it may still be possible to reduce world hunger through programs that feed the poor during crises and by investing in agricultural inputs such as fertilizer and improved varieties that can dramatically increase yields (*2*). Improved environmental monitoring and prediction systems can provide more effective early warnings, which may help governments to take action to preserve the thin agriculture production margins by which many make ends meet (*7*). Early warning systems involve extensive climate monitoring and prediction tools that could be used to enhance agricultural development programs. Crop insurance programs that are triggered by remote sensing data products may ensure farmer's livelihoods even in drought years. Investments in improved seeds and varietals and an augmented use of inorganic fertilizer (*2*, *6*) can increase yields. Improved local governance, reduced developed-world agricultural subsidies, and more nuanced food aid policies that protect local markets could together produce rapid improvements in food access and availability, reducing hunger while providing for more people.

30% of farmers in developing countries are food-insecure; the work of Lobell *et al.* suggests that climate change may impact these undernourished communities by decreasing local yields while contributing to a global increase in commodity prices through significant global reduction in the production of corn, wheat, and rice. Despite these challenges, the very low agricultural productivity of food-insecure countries presents a great opportunity. Transform these agricultural systems through improved seed, fertilizer, land use, and governance, and food security may be attained by all.

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