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Creation and Capture of Innovation Returns for Intensive Urban Agriculture Systems

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ABSTRACT

Controlled environment agriculture (CEA) allows food plants to be reproducibly grown under conditions of optimal light, temperature, nutrition, and pest control. Space requirements are minimal, and so CEA is ideal for urban areas. Benefits are clear, but the long term economic viability of this new agricultural system is uncertain. We formalize the strategy space for innovation in CEA and discuss the extent to which it is served by investments in public sector agricultural research. We also present a unifying model of the relationship between the organoleptic and other food attributes desired by consumers and the suites of component technologies and business models capable of delivering these attributes via CEA.

Keywords: *agricultural innovation; controlled environment agriculture; modeling; strategy*

Enabled by rapid technological advancements, complete control of the growth environment for food plants has become a recent agricultural option. Controlled environment agriculture (CEA) relies on artificial lighting, not as a supplement to the sun, but as its replacement. It dispenses with soil, so that plants are supported by fabrics, held in small plastic containers, or anchored in other artificial substrates. Roots can be misted hydroponically with a nutrient solution or allowed to grow aquaponically in aerated solutions. By its very nature, CEA also simplifies exclusion of pests. Day length, the intensity and spectrum of light, temperature regimes, relative humidity, and air movement all can be controlled precisely, allowing for vast amounts of data points to be collected, analyzed, and used to continuously optimize the growing system. And if the surfaces used for growing plants are stacked vertically, immense efficiencies in space utilization can be achieved, allowing for large scale food production in densely populated urban areas (Despommier, 2010).

None of the individual components of CEA is unique, and indeed, some have been developed and used extensively in partially controlled plant growth environments such as greenhouses. Yet when assembled together, the components of CEA generate a growth system with novel features that create correspondingly novel opportunities for agricultural innovators. Chief among them is the possibility to offer consumers an array of food products with desirable nutritional, health, and organoleptic attributes by matching agriculture's longstanding ability to precisely control plant genetics with the heretofore unachievable: a corresponding capacity to precisely control the environment. These relationships can be represented by the expression $A = G \times E$, which emphasizes attributes (A)

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as the end goal and the product of genetics (*G*) and the environment (*E*) as the means to achieve it. To the extent that consumer priorities for *A* evolve over time, *G x E* can respond—flexibly, reproducibly, and on-demand.

The potential benefits of CEA remain clear, even as agricultural innovators continue to invest and experiment. The long-term economic viability of CEA is nonetheless uncertain, and this has stimulated us to investigate three factors likely to contribute to the ultimate success of these systems. Although we do so within the context of the United States, we expect that our findings will be broadly informative.

The first factor relates to the innovation ecosystem that the initial entrants into CEA have begun to create. What can we learn from early innovators? Who are they, what experiences and motivations drive them, and are there any patterns that could provide insights into the factors that both impede and enable success? We have parallel interests in the extent to which the CEA innovation ecosystem is served by the stream of research emanating from the two public sector institutions with responsibility to advance agriculture in the United States: the nation's network of land grant universities and the federal Agricultural Research Service, which maintains a geographically distributed (and in many cases land grant university-associated) network of research facilities in all 50 states. Both institutions receive base annual federal appropriations (land grant universities also receive matching state funding), but they also benefit from grant funding awarded by the US Department of Agriculture on a competitive basis (Alston et al., 2009).

By virtue of its funding model and geographically distributed structure, the US public agricultural research portfolio tends to be oriented toward local and regional problems. The portfolio also tends to be organized around traditional agricultural disciplines such as horticulture, agronomy, soil science, agricultural engineering, plant pathology, agricultural economics, and entomology. We think it important to understand the tension between these features of the current model and the research needs of CEA, which are subject to fewer geographical constraints and reliant on emergent technologies and systems approaches.

Second, we present a unifying economic model of CEA innovation that defines and then examines three related spaces that are designated according to Lancaster (1966). They are: technology or I-space (changes to the production function, business model, and transaction costs), product attribute or z-space space (what matters to the consumer), and goods or Q space (where the score is kept on revenues, market share, return on assets, and profits). These relationships are illustrated in Figure 1, which shows the simultaneous relative positions of four existing firms in technology or I-space and product attribute or z-space.

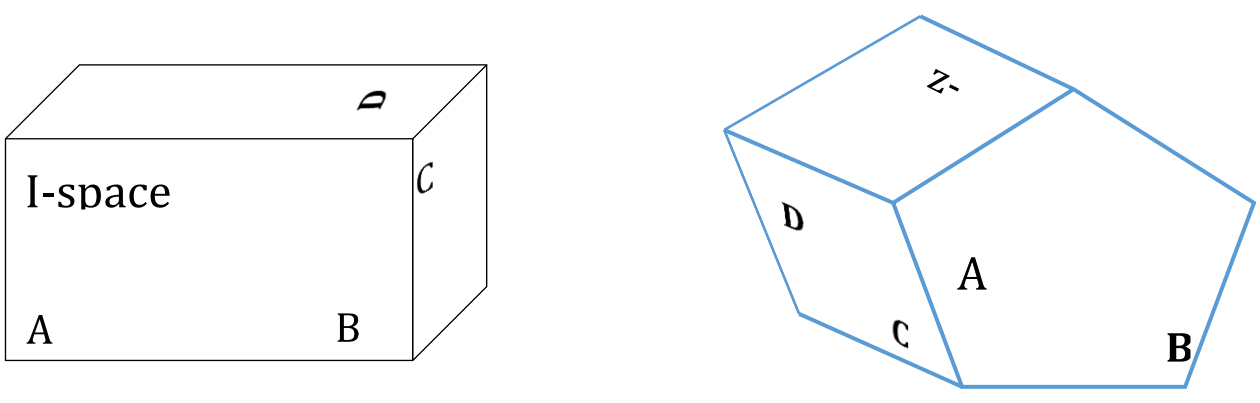

Figure 1. Representations of two multi-dimensional spaces: product attribute space (z-space) in *m* dimensions and technology space (I-space) in *n* dimensions. The positions of four incumbent firms in each space are indicated.

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We model innovation to be new production function entry into an existing industry, regardless of whether the innovation occurs in an incumbent firm or a new firm. The model introduces firm E into both spaces, relatively close to or far from the other competitors depending upon the attribute profile of the new products (z-space) and the production technology and firm structure (I-space). Innovation can occur in either or both of the two spaces (jointly, the *strategy space* for each firm) as depicted by the example below in Figure 2, which positions Firm E distant from its competitors.

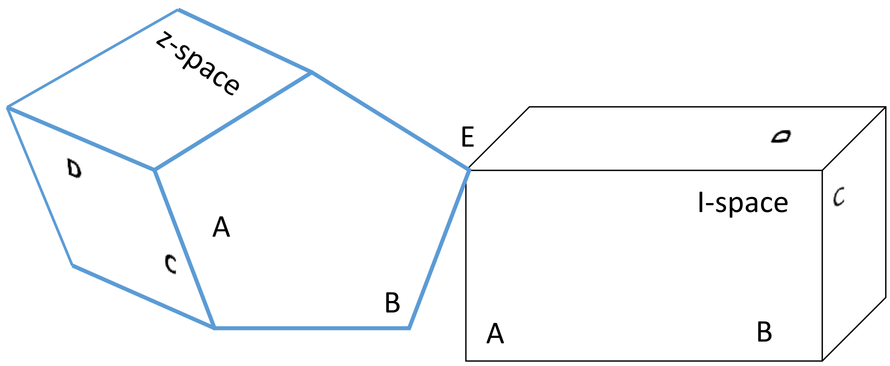

Figure 2. Putative entry point of a new competitor – Firm E – seeking a position distant from incumbent firms simultaneously in z-space and I-space. (Firm E at tangency of vertices.)

Formally, we have a networked industry of *r* firms characterized as *r* production functions at some time *t*:

(1) $\{F_t^1, F_t^2, F_t^3, \ldots, F_t^i, F_t^j, \ldots, F_t^r\}$,

and for Firm 1 in the industry, its output in time *t* is a function of its inputs/technology:

(2) $X_t^1 = F^1(\vec{I}_t^1)$, where the term in the parentheses is the vector of inputs.

The firms in the industry compete by providing qualitatively different products to buyers. We extend consumer theory by drawing from the seminal work of Lancaster (1966, 1991), who argues that the variables in the utility function are not the goods themselves (X^i), but the characteristics of the goods and the *services* they render. The dimensionality of attribute space is R^m. Following Lancaster, each product is characterized by a vector of attributes of interest to buyers, which create value.

(3) $X_t^1 = G_t^1(\, z_1^1, z_2^1, \ldots, z_j^1, \ldots)$, or, in vector shorthand, $X_t^1 = G_t^1(\vec{Z}_t^1)$,

where G_t^1 is the quality function—the production outcome—that relates the individual attributes z_j to the output of Firm 1. We expect the products of firms *i* and *j* to be qualitatively distinct:

(4) $G_t^i(\vec{Z}_t^i) \neq G_t^j(\vec{Z}_t^j)$, where $z_i \in R^m$.

Innovation occurs in both F_t^1 and G_t^1, following the five genres of innovation as defined by Schumpeter (1926). The resultant changes in product attributes and production technology cause consumers to re-evaluate their purchase behaviors in period t+1. This reallocates purchases in goods space and consequently revenues, profits, and market shares are redistributed among the incumbents and the new entrant. Should the innovation be sufficiently large, we would experience Schumpeter's "creative destruction" with one or more incumbents swept away in "the perennial gale."

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Given this formal model of innovation, the emergent nature of the industry, and the current state of CEA component technologies, we can locate incumbent firms rather easily in both product attribute and technology space. The component technologies, especially in LED lighting, have to date been a rather limited sub-space for innovation. However, nearly all of the current complete systems are one-off designs, especially with respect to housing and environmental controls. We contend that the most interesting innovation sub-space lies in choice of genetics for CEA and the efficient co-specialization of genetics with the other subsystems. To our knowledge, these relationships have not been systematically exploited.

The above considerations lead to the third factor that we consider for the future: the implications of CEA for organizing the science and the resultant innovations needed to facilitate successful entry into the intensive and competitive food production marketplace that will characterize the future. In theory, successful entry should be driven by optimization across component technologies that are designed and implemented as complementary, co-specialized subsystems. Who can and will do this? Can public sector entities manage this process, assuming the role of system innovator and capturing some of the value created by entrepreneurial organization? Or will the value created by innovation necessarily flow to others such as those providing the significant amounts of equity capital that are required for CEA?

Most large research universities have established entities to capture value from science and invention created on campus. They typically employ a set of common strategies for value capture: incubation of start-up firms based on inventions, licensing of technology to existing firms, or outright sale of intellectual property. This approach has achieved reasonable success for stand-alone inventions driven by disciplinary science. But what of complex system-level innovation that combines and co-specializes inventions from several disparate disciplines, as is the case for CEA: agriculture (plant genetics and nutrition), engineering (environmental control), information technology (data management and interpretation), and business (consumption, marketing, and economics)? Surmounting these boundaries has not been a traditional strength of research universities, despite the co-location of the relevant disciplines. Although the necessary incentive alignment, management, and rewards systems are typically absent in research universities, we believe that there is no public institution better positioned to take on the role of Schumpeter's system innovator in this emerging industry.

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