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A framework for assessing the vulnerability of food systems to future shocks

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Abstract

Modern society depends on complex agro-ecological and trading systems to provide food for urban residents, yet there are few tools available to assess whether these systems are vulnerable to future disturbances. We propose a preliminary framework to assess the vulnerability of food systems to future shocks based on landscape ecology's 'Panarchy Framework'. According to Panarchy, ecosystem vulnerability is determined by three generic characteristics: (1) the wealth available in the system, (2) how connected the system is, and (3) how much diversity exists in the system. In this framework, wealthy, non-diverse, tightly connected systems are highly vulnerable. The wealth of food systems can be measured using the approach pioneered by development economists to assess how poverty affects food security. Diversity can be measured using the tools investors use to measure the diversity of investment portfolios to assess financial risk. The connectivity of a system can be evaluated with the tools chemists use to assess the pathways chemicals use to flow through the environment. This approach can lead to better tools for creating policy designed to reduce vulnerability, and can help urban or regional planners identify where food systems are vulnerable to shocks and disturbances that may occur in the future.

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1. Introduction

Events such as September 11th and the SARS outbreak in Canada and South East Asia highlight that modern urban society is vulnerable to seemingly remote threats [35].

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46 One area of concern is the food system that provides urban residents with a regular and
47 abundant supply of affordable nutrition [47]. This food system depends on a number of
48 things: a functioning global market, open trade routes, affordable energy, and stable
49 weather conditions that allow crops to flourish. There is reason to suspect that many of
50 these factors may not be secure in the future. For example, there is considerable debate
51 about the effect that international trading agreements will have on food production. Some
52 argue that although global trade in agricultural commodities benefits wealthy urban
53 residents, it hurts poorer members of society and deepens poverty in many regions
54 [53,54,87]. Others argue the opposite [5,7,50]. Similarly, there is an on-going debate
55 about the impact that climate change may or may not have on the earth's ability to
56 produce food [1,15,51,66,72,81,94], and the environmental and social impact of
57 transporting food around the globe [40]. Some assessments conclude that modern urban
58 society puts unsustainable demands on the planet's productive capacity, and that we have
59 exceeded the earth's carrying capacity [78]. Others argue that since society has
60 developed agricultural technologies that allow a small number of people to produce an
61 unprecedented amount of food, we should be optimistic about the potential of future
62 technological innovation [13,88].

63 These various contradictions suggest that we have only a poor ability to predict the
64 future of something as complex as the food system. As a result, some scholars have moved
65 away from trying to predict the future of global food security, focusing instead on the
66 adaptive capacity of individual communities. This approach has become more common in
67 the climate change literature, where scholars have invested considerable energy into
68 defining resilient communities, social capital and adaptive capacity as a way of identifying
69 regions that may be adversely affected by possible future environmental fluctuations
70 [2,18,41,79,91]. In many cases, this approach has generated long lists of social, economic,
71 political and environmental variables that must be assessed in order to evaluate social
72 capital or identify resilient communities [9,11,18,75,76]. Although academically very
73 interesting, this approach implies that everything social and political must be considered
74 [94]. This provides a cumulative list that is too complex to be useful in developing policy-
75 making tools [28].

76 We are faced with the dilemma of how comprehensive a model to build—one with
77 many variables that ends up as a qualitative description, or one with a few key variables
78 that acts quantitatively but lacks comprehensiveness. The Panarchy framework, which
79 emerged as a synthesis of considerable fieldwork by a group of landscape ecologists,
80 provides a compromise in that it offers simple diagnostics of complex systems [37,38,43,
81 46]. In this paper, we will explore how Panarchy can be applied to the food systems on
82 which urban communities depend to help determine future vulnerability.

85 **2. Panarchy: a vulnerability framework from landscape ecology**

87 Landscape ecologists are particularly interested in a framework that helps establish the
88 vulnerability of systems [2,918,42]. This small group of scholars observed that
89 disturbances—discrete events such as fires, storms, pest outbreaks, floods or droughts
90 that disrupt the structure of an ecosystem [6,93]—are common and allow ecosystems to

regenerate by releasing accumulated nutrients. By studying such diverse ecosystems as the everglades and the boreal forest, these scholars have been able to identify three general characteristics of ecosystems that are likely to be significantly affected by disturbances [37,38,43,45,46].

The first characteristic is the ‘inherent potential of a system that is available for change’ [43 p. 393], which can be defined loosely as ‘wealth’. In a forest ecosystem, a rich foliage or high biomass that indicates a mature system would represent wealth. A wealthy system is more liable to be affected by a disturbance than a non-wealthy system, largely because it has more resources that may be affected by the disturbance. The second characteristic is the degree to which a system can control external forces. This can be measured by assessing how connected the components of the system are to each other and to the external world. The third characteristic is the diversity of the system. Diversity provides a way of assessing the capacity of the system to adapt to external forces as diverse systems are better able to tolerate a wide range of environmental conditions than simple systems [8,32,59].

Using this terminology, ecosystems recover after a disturbance by accumulating wealth (in this case biomass). As wealth builds up, connectivity increases as ecological niches are filled in, and diversity first rises and then drops as the more successful species out-compete less successful species. After a period, it is possible for a system to become so well connected, so wealthy, and so specialized that an external event (such as a wind storm, forest fire, or pest outbreak) may trigger a quick release of the accumulated capital, and cause the system to revert to a less organized state. When this happens the system may collapse entirely and enter a new phase of reorganization that leads again to wealth accumulation, increased connectivity and reduced diversity.

This description of wealth accumulation, decline in resilience, release of capital and system recovery has been formalized as the Panarchy framework by Gunderson and Holling [37]. The Panarchy framework has been utilized effectively to examine the impacts of disturbance between nested spatial scales, from the local to the global level. This framework suggests that disturbances may cascade up and down landscape scales, precipitating further disturbances and triggering collapses in neighbouring systems. This may be particularly true if higher levels in the Panarchy “...have also accumulated vulnerabilities and rigidities...” [43 p. 398]. An ecological example is when a small ground fire spreads to the crown of a tree, which then can cascade up to the stand, forest or landscape level depending on the connectivity, wealth, and diversity of the site in question.

While the majority of the scientific work done with the Panarchy framework relates specifically to natural or managed ecosystems, preliminary evidence suggests that these three characteristics may also help illuminate vulnerability in social systems [44]. There are a number of published studies that explain the effect of historic disturbances on human communities in terms of wealth, connectivity and diversity. The Irish Potato Famine, for instance, resulted when a large number of communities depended entirely on an agro-ecosystem that was biologically wealthy, connected and had low diversity [26]. Similarly, Berkes and Folke use this model to draw parallels between the Hindu caste system and the evolution of ecosystems [10].

The benefit of this approach is that it provides us with a small number of key variables that help uncover vulnerability. However, the three characteristics that determine

136 vulnerability in the Panarchy framework, can be defined in a number of ways; for example,
137 in some social contexts wealthy, well connected communities are better able to adapt to
138 unanticipated problems than non-wealthy, isolated groups. Using Panarchy to identify
139 insecurities in the food system require clearer methods to assess wealth, diversity and
140 connectivity.

143 3. Understanding wealth using an entitlement framework

144
145 From an ecological perspective, the Panarchy Framework considers a wealthy system
146 one where there is a great deal of biological productivity. Rich biomass, high nutrient
147 loads, and productive plant growth would all be indicators of wealthy systems. This wealth
148 allows disturbances to have a much larger impact than they would if the disturbance
149 occurred in a less wealthy system. For example, pests reproduce much more effectively
150 and can devastate much larger areas in biologically wealthy systems. Biologically
151 productive regions also require much more water, increasing the impact of drought.
152 Finally, ecosystems with high biomass are more likely to be affected by fires since there is
153 more fuel available.

154 To assess the biological wealth of a region, it is possible to measure net primary
155 productivity, or the amount of calories that green plants produce out of sunlight. Net
156 primary productivity in most ecosystems has been traditionally limited by water and soil
157 bound nutrients available for plant growth. However, the advent of modern agricultural
158 technologies has extended or removed many of these limits. For example, nitrogen is
159 abundant in the atmosphere in the form of N_2 , but is unavailable for plant growth until the
160 bond between the two nitrogen atoms is broken, and a new bond formed either with
161 hydrogen (to create ammonium, NH_4) or oxygen (to create nitrate, NO_3). In nature, there
162 are only two ways to achieve this, lightening or the enzyme nitrogenase that is produced by
163 some bacteria. Historically these two mechanisms would 'fix' approximately 120 Tg N
164 globally each year [89]. The lack of nitrate and ammonium in most ecosystems led the
165 19th century chemist Justus von Liebig (1803–1873) to develop the law of the minimum,
166 which states that plant growth is limited by the nutrient least present in the soil. The limit
167 imposed by plant available nitrogen was lifted early in the 20th century when chemists
168 Fritz Haber (1868–1934) and Carl Bosch (1874–1940) developed a way to combine
169 hydrogen and nitrogen at high temperatures to form ammonium. Today, the Haber-Bosch
170 process creates more plant-available nitrogen than all natural sources, making agricultural
171 ecosystems much more wealthy and, therefore, much more vulnerable to the impact of
172 shocks or disturbances.

173 In human communities, wealth has a very different meaning. While the Panarchy theory
174 suggests that biological wealth is a characteristic of vulnerability, decades of development
175 work illustrate that social or financial wealth help communities adapt to changes
176 [12,65,77,92]. If we are to apply the Panarchy framework to food systems, we need to
177 distinguish between ecological wealth that is measured by biomass and is fixed until
178 released by a disturbance, and social wealth that has the potential to change forms based on
179 the needs of the person who owns it (e.g. a wealthy person can use their capital and invest
180 it in ways that reduce vulnerability).

181 The Nobel Prize winning welfare economist Amartya Sen suggests that in order to
182 understand to the role of social or financial wealth in food systems we need to evaluate
183 all the various strategies that a community or household uses to obtain food [20,85,86].
184 Sen identified three strategies or food entitlements: (1) direct entitlements whereby a
185 family produces their own food; (2) indirect entitlements whereby a family works for a
186 wage and then obtains food from the market; or (3) a transfer entitlement whereby food
187 is obtained through charity or gifts (such as money sent from family members abroad).
188 Problems in the food system arise when a person's or a community's entitlement is
189 disrupted and they cannot switch to another method of obtaining sustenance. The
190 entitlement theory is useful because it disaggregates the reasons why a person or group
191 may become vulnerable to hunger [19]. It also focuses our attention on food systems
192 where people do not have the ability to switch to alternative entitlements if their prime
193 entitlement is disrupted.

194 Although entitlement analysis has traditionally been applied to households, the
195 concepts can also be used to assess the food system at the urban scale. Food produced in
196 and around a city can represent a direct entitlement; food imported from distant regions
197 using the global market is an indirect entitlement. Food aid—the 1948 Berlin airlift or the
198 containers of grain sent to Ethiopia in the early 1980s—would be a transfer entitlement.
199 For example, since 1989 Cuba has switched from an indirect entitlement based on trade
200 with the USSR to a direct entitlement based on self-sufficiency after the fall of the Soviet
201 Union [82]. Assessing the potential for direct entitlements will involve assessing how
202 much land is available for cultivation, and whether urban residents have the technological
203 know—how to produce food in adequate amounts. Assessing the potential for indirect
204 entitlements would involve examining the financial wealth present in a community and
205 how equitably it is distributed. Assessing possible transfer entitlements would require
206 evaluating welfare programs, as well as family networks that ensure communities survive
207 in times of hardship [39]. In the food system, increasing the number of food entitlements
208 increases the human dimension of wealth, which helps reduce vulnerability.

209
210

211 **4. Understanding connectivity using pathway theory**

212

213 Panarchy's second characteristic of a vulnerable system is one that is tightly connected
214 across the landscape. Connected systems allow disturbances to pass quickly from one
215 individual to the next and from one landscape scale to the next. For example, in a tightly
216 connected ecosystem, pest outbreaks can swiftly spread across large areas. The spread of
217 Sudden Acute Respiratory Syndrome (SARS) from rural China to South East Asia and
218 then into Canada highlights why connectivity is an important aspect of vulnerability.
219 There are many ways that connectivity affects the food system. For example, large fields,
220 such as wheat fields on the Great Plains or Canadian prairies, are prone to pest outbreaks
221 because individual plants are very close together and contiguous fields link large areas into
222 single types of landscape. One method to evaluate connectivity is to assess the pathways
223 that a disturbance might take through the landscape to affect urban food systems. Chemists
224 and physicists have taken this approach to deal with the complex way in which chemicals
225 disperse through the environment.

226 Attempts to understand the environmental fate of chemicals have been ongoing for over
227 a century. In 1901, G.N. Lewis introduced the concept of fugacity, or the fleetingness of
228 chemicals, as a convenient way to describe thermodynamic equilibrium criteria [56]. The
229 concept builds on the thermodynamic equilibrium that exists as chemicals pass between
230 different phases (i.e. solid to liquid to gas), but also includes complex structures and
231 mobile elements of the environment. These structures, or transport media, involve both
232 non-living structures such as the atmosphere, oceans, lakes, rivers, sediment and earth
233 (each of which exists in a different chemical phase), as well as living elements or biota,
234 which includes all plants and animals. Over the past two decades, the fugacity concept has
235 been applied to mathematically describe the rates that chemicals move from one transport
236 medium to another [58].

237 By focusing on transport media, we can evaluate how urban food systems can be
238 affected by remote events and track the outputs of human activity, including energy,
239 chemicals, biota and pathogens, from their release to their ultimate fate. This makes it
240 possible to identify future vulnerabilities in human systems, and ultimately should allow us
241 to prevent the problems by changing our practices at the source.

242 Transport media are defined by a variety of factors. Mackay [58] describes transport
243 media as either continuous (the atmosphere, water in the form of lakes and oceans, and
244 earth) or discontinuous (terrestrial and aquatic flora and fauna). The mobility and resultant
245 reach of transport media is also variable; the atmosphere is highly mobile and exists on the
246 global scale, while bedrock is exceedingly stable and can be considered to exist only on the
247 local scale. The accessibility of these media to anthropogenic chemical transfer varies.
248 Rock buried deep beneath the earth may be considered virtually inaccessible, while the
249 atmosphere is highly accessible. Finally, certain transport media are contiguous; the
250 atmosphere touches terrestrial soil and biota constantly, but rarely comes into contact with
251 deep water, aquatic plants, or ocean sediment [58]. The ultimate environmental fate of all
252 anthropogenic emissions is thus controlled by the characteristics of the transport media
253 into which they are released.

254 The food system that supplies our urban centres is an excellent example of a chain of
255 pathways that link city dwellers to the greater environment. For example, dioxins are
256 produced in many industrial processes such as waste incineration [16]. Since these
257 chemicals are quite toxic, these processes are isolated from human settlement. Cow's milk
258 that is produced within the vicinity of these industrial activities, however, may contain
259 these dioxins in small amounts [57]. Once consumed by other organisms, dioxins bio-
260 accumulate up the food chain, eventually causing serious human health problems [71,74].
261 Therefore, pathways through the food system can bring undesirable chemicals into the
262 urban setting.

263 The pathways approach to connectivity can shed new light on phenomena that until
264 now have been thought natural in origin. For instance, the droughts experienced in the
265 Sahel region of Africa in the 1980s led to significant famine in countries such as Ethiopia
266 and Sudan. Recently, studies have shown that anthropogenic sulphate aerosols released
267 from power stations and industrial facilities in both Europe and North America may have
268 led to shifts in tropical rainfall patterns that caused or exacerbated these droughts [68,83].
269 This example illustrates the global reach of the atmosphere as a transport medium. The
270 impact of human activities is, in this case, indirect, and cause and effect are more difficult

271 to prove. It is only through a careful analysis of the fugacity of the chemicals in question,
272 and through models of their environmental fate, that the link the African famine and
273 industrial activity in Europe and North America were identified.

274 A brief case study illustrates how the pathway approach can identify vulnerability in
275 urban food systems. In Walkerton, Canada, an estimated 2300 people became ill and seven
276 died when bacteria infected drinking water in the spring of 2000. This incident was
277 eventually blamed upon a multiplicity of failures in the water safety system [48]. The
278 source of the Walkerton outbreak was found to be a combination of *Escherichia coli* and
279 *Campylobacter jejuni* pathogens found in cattle manure from a local farm. The manure
280 had been spread on fields overlying a shallow aquifer near one of the town's wells
281 immediately before a period of intense spring rainfall [70]. The rain-soaked fields
282 provided a transport mechanism that carried the pathogens through the soil and into the
283 groundwater. Although warnings that this aquifer could be affected by surface activities
284 had been circulating for over 20 years, it continued to be used for drinking water,
285 agricultural practices did not change, and the town had not taken the recommended step of
286 safeguarding the aquifer. Interestingly, recommendations from the subsequent govern-
287 mental inquiry dealt with monitoring and safety mechanisms rather than stopping the
288 practices that caused the problem in the first case. An approach to vulnerability that
289 explicitly evaluates environmental pathways should ensure that these sorts of root causes
290 are addressed by policy.

291
292
293

294 5. Understanding diversity using portfolio theory

295

296 According to Panarchy theory, diverse systems are better able to withstand shocks than
297 simple ones [4,8,32]. This characteristic is based on the observation that there is a
298 correlation between diversity and stability in ecology [24,34]. As a result, for the last ten
299 years promoting biodiversity has been at the centre of many food and agricultural policies
300 around the world [3,33,49].

301 Ironically perhaps, the modern environmentalist's appreciation of diversity is decades
302 behind the ranks of conservative business people, financiers and bankers who
303 have preached the need to maintain diversified portfolios for much longer. Modern
304 Portfolio Theory—the academic way of saying “...don't put all your eggs in one
305 basket...”—provides investors with a framework that systematically links diversification
306 of assets to risk [60,61]. Thanks to Modern Portfolio Theory, we can prove that
307 diversification reduces investment risk on a portfolio level and allows investors to achieve
308 superior risk-return combinations. Within this context, risk is defined as the standard
309 deviation of expected returns, and risk exists whenever the future return cannot be
310 predicted with certainty. Modern Portfolio Theory shows that diversification is useful
311 when three conditions are met: (1) there is more than one possible investment at any given
312 time; (2) these investments are subject to risk; and (3) that the same economic conditions
313 do not affect all investments equally (for example, when the stock market is doing well, the
314 bond market might do less well and vice versa). More formally, economists describe this
315 as ‘imperfectly correlated or uncorrelated risk’.

316 The link between Modern Portfolio Theory and the diversity of natural assets such as
317 different crops has only recently been systematically established [21–23]. If we consider
318 urban regions as investors and different food entitlements as investments, we can apply
319 this same logic to the food system. For example, the urban food system meets all three
320 conditions applicable to Modern Portfolio Theory. First, it is possible to have more than
321 one food entitlement option at any given time: a city can trade with a number of different
322 regions, import a wide range of crops and maintain a diverse selection of locally grown
323 produce. Second, future crop yields are uncertain [52,73]. As a result, any food entitlement
324 is subject to risk. Third, the risks that different crops and different entitlements are exposed
325 to are not perfectly correlated [36,55]. In other words, the conditions that will lead to the
326 failure of one food entitlement will not necessarily affect other strategies [52,67].

327 To apply Modern Portfolio Theory to risks in the food system it is important to
328 differentiate between systematic and unsystematic risks. Systematic risks affect entire
329 systems, regardless of the level of diversification within a portfolio. For example, a general
330 decline of the stock market (a systematic risk) affects all portfolios no matter how well
331 they are diversified. A biological systematic risk would be a change in the global
332 environment that limited food production everywhere around the world. Diversification of
333 entitlements does not eliminate this sort of risk. Unsystematic risk, on the other hand, is
334 risk that affects only individual elements. According to Modern Portfolio Theory, it should
335 be possible to reduce the unsystematic risk within the food system by having diverse
336 means of access to food, such as relying on crops with different ecological characteristics,
337 purchasing crops that grow in very different regions in the world, and maintaining a
338 mixture of trading links and local food production.

339 Modern Portfolio Theory provides tools to assess unsystematic risks by calculating
340 covariances between all elements of a portfolio. Elements are expected to covary if the
341 same conditions affect each element in a similar fashion. For example, because cabbage,
342 broccoli and cauliflower are all crops from the family *brassica* they are vulnerable to
343 similar pests and have similar environmental requirements. These crops would be
344 considered to have a high covariance and offer little diversification to reduce risk. Crops
345 from other families would be expected to have a low covariance with the crops of the
346 family *brassica* and would, therefore, be well suited to diversify the risk.

347 Portfolios in the stock market are constructed in a similar way. The lower the
348 correlation of a stock with the other stocks of the portfolios the better. Low-covariance
349 stocks allow investors to diversify portfolio risk, whereas high covariance stocks, i.e.
350 stocks that fare well in raising markets and vice versa, add risk. Portfolio managers are,
351 therefore, interested in the correlation between stocks rather than the risk of individual
352 stocks. They seek to put stocks in a portfolio that are not correlated. From a portfolio
353 perspective, the risk of a stock is therefore defined by the degree to which it covaries with
354 other stocks rather than by the degree to which it fluctuates independently.

355 The future of a portfolio management of our food supply will obviously depend on
356 whether a portfolio effect that reduces risk can be observed in practice. An American study
357 comparing the relationship between the variability of wheat yields with the size of the
358 cultivated area shows that an agricultural portfolio effect of this type is more than a
359 theoretical construct. All other things being equal, with a larger cultivated area the
360 portfolio size should increase and the portfolio variability fall. This portfolio effect can in

361 fact be observed [84]. Portfolio theory can, therefore, help to assess and manage
362 biodiversity in general and agro-diversity in particular. Applying Modern Portfolio Theory
363 to the question of food entitlements provides the formal framework and tools to measure
364 and assess the role that diversity plays in generating vulnerability in the urban food system.
365

366 6. Discussion: policy and institutional response to reduce vulnerability

367
368
369 Modern agriculture, on which the cities of the world depend, is a system that is wealthy,
370 tightly connected and non-diverse. For example, western nations rely on just one crop—
371 wheat—to provide the vast majority of our nutritional needs. This crop is usually grown as
372 a continuous monoculture, or as a part of a relatively simple crop rotation, in just a few
373 primary areas including the Ukraine, the Great Plains, and the Canadian Prairies. From the
374 perspective of the Panarchy framework, this is a highly vulnerable system—“...an
375 accident waiting to happen” [43, p. 396]—and pro-active policy should take steps to
376 increase diversity while reducing connectivity and wealth. However, unless this is
377 carefully done, this sort of strategy could result in large increases in the price of food since
378 wheat production would be diversified into regions less climatically suited to this crop. It
379 would probably also mean that forests and wetlands could be converted into marginal
380 agricultural land in regions that do not currently produce wheat, and this might result in
381 habitat loss and soil degradation.

382 The challenge is that urban citizens in the developed world depend on the biological
383 wealth that comes from modern farming techniques, and the reason grain farmers can meet
384 our demand for food is because this simple and connected system allow a small number of
385 people to plant, tend and harvest vast areas, maximizing biological potential and directing
386 this productivity into a limited range of outputs [29,30]. The tremendous wealth in the
387 present-day food system is a result not only of specialization and connectivity at the farm
388 level, but also at the regional level, where large areas achieve economies of scale by
389 producing only those commodities they have a comparative advantage in [31,64]. This
390 means that crops can be gathered, processed, turned into food and shipped to cities, all at a
391 low economic cost given regional connectivity and homogeneity. Therefore, modern
392 agriculture exists because it is wealthy, connected and non-diverse.

393 Unfortunately, this means that from an ecological perspective, this is a vulnerable system
394 and we can expect that future disturbances may cause significant collapses. Armed with the
395 knowledge that we depend on a food system that has all the characteristics of an ecosystem
396 vulnerable to serious disruption we are left with the question: what should we do? We feel that
397 the Panarchy Framework helps provide answers to this question. For example, to increase the
398 diversity in the food system while maintaining productivity, policy could ensure that urban
399 regions have access to a number of different entitlements. This would probably involve
400 providing incentives (such as tax breaks, research, education and promotion) for people to
401 engage in urban agriculture. While urban agriculture is a viable activity in some parts of the
402 world [14,62,63], in most Western countries agriculture pays notoriously poorly, so unless
403 one chooses to engage in urban agriculture for personal reasons—the Mediterranean
404 communities in Canada are famous for highly productive urban gardens [27]—there are few
405 economic incentives to produce food in cities [25]. Pro-active policy could provide these

406 incentives. Second, although farms in peri-urban regions in the West do not make short-term
407 economic sense since land is more valuable for urban development than agriculture,
408 maintaining peri-urban agriculture is a vital strategy to maintain diversity in the food system.
409 Finally, allowances must be made for poor communities who do not have the financial or
410 social wealth to access these different entitlement options. At the very least this would entail
411 ensuring that transfer entitlements are available for the most needy members of society, but
412 could also include a range of food aid programmes.

413 Another strategy to decrease vulnerability in the food system would be to consciously
414 and deliberately maintain trading links with numerous regions around the world. Since
415 problems like climate and ozone depletion will have unpredictable effects on food
416 production [69,72,80,90] having multiple trading partners will help minimize unsystematic
417 risks associated with global environmental change. Increased trading, however, will
418 also increase connectivity and this makes the food systems more vulnerable to pathogens
419 or diseases. Therefore, this strategy must be combined with mechanisms to monitor food
420 trade patterns and food movement around the world. Reliable inventories of food
421 movements, combined with the pathways approach proposed here, would provide
422 scientific guidance on how to define areas that should be quarantined, based on the
423 transmission pathways a disease might take. This approach is more refined than simply
424 imposing nation-wide sanctions if problems emerge. For example, after a single case of
425 *bovine spongiform encephalopathy* (BSE) in Alberta, Canada, the US and other countries
426 banned all Canadian beef [17] even though there was more connection between the cattle
427 industry in Alberta and the North Western U.S. than there was between Alberta and
428 Eastern Canada. If policy makers had identified the pathways open to diseased cattle from
429 Alberta, Idaho, Washington and Oregon would have been immediately quarantined while
430 Eastern North America would have been unaffected. Instead, farmers across Canada were
431 hurt financially, and until a cow with BSE that originated in Canada appeared in a herd the
432 U.S. herd, American policy makers did not acknowledge any threat.

433 The framework laid out here is preliminary. The authors are under no illusion that it is
434 possible to characterise all urban systems in terms of wealth, diversity and connectivity, let
435 alone explain all types of vulnerability using these three basic variables. For example, in
436 the developed world, poverty, social isolation and disease are more significant and
437 immediate causes of vulnerability than the risks of depending on large, productive wheat
438 monocultures. Nevertheless, we feel that this approach provides a certain degree of
439 guidance in understanding how the food system that Western cities depend on may be at
440 risk even though problems have yet to appear. If used, therefore, this approach should be
441 considered a way of flagging troublesome areas for careful study and analysis.

442 443 444 **7. Conclusion**

445
446 Some threats that cities face, such as earthquakes, can be dealt with through the
447 technical expertise of the engineers who build the infrastructure that physically surrounds
448 us. Other threats (September 11th and the SARS outbreak) illustrate that even the best
449 technical know—how will not address impossible to predict remote threats. Despite this
450 complexity, we still need tools to help ensure cities have the capacity to withstand major

451 disturbances. One set of tools includes the global circulation models used to predict
452 climate change. Due to scientific uncertainty, it has not been possible thus far to apply
453 these models effectively at the regional level. A different approach is to assess whether a
454 community has the capacity to adapt to change rather than trying to predict change itself.

455 To help assess the capacity to adapt to change, we propose using the Panarchy
456 framework, a theory from landscape ecology that accounts for the impact of disturbances on
457 ecosystem using just three variables (wealth, connectivity and diversity), as a way of
458 assessing whether the urban food system is vulnerable to disruption. The benefit of the
459 Panarchy framework is that it strives to balance complex descriptive models and more
460 simplistic deterministic ones by applying a set of principles to expose vulnerability.
461 Diversity is probably the easiest of the three characteristics to apply to urban systems. Just as
462 an investment advisor would caution against a portfolio that only contains a small number of
463 investments, policy should focus on diversifying the sources of food an urban region
464 depends on. If a system is tightly connected to the region around it, disturbances can quickly
465 spread and an area will be vulnerable to remote threats. One way to assess connectivity is to
466 evaluate the various pathways of material, labour and capital that flow through an urban
467 region. By tracking these pathways, it may be possible to safeguard cities by changing our
468 practices at the source. Wealth is the most difficult of the three concepts to apply to the urban
469 food system. While landscape ecologists consider biological wealth a characteristic of
470 vulnerability, since a rich supply of biomass is vulnerable to pest outbreaks, financial wealth
471 can reduce vulnerability. For example, wealthy people can afford to build homes that do not
472 collapse during earthquakes. Therefore, to apply wealth as a characteristic of vulnerability,
473 we must first distinguish between biologically wealthy ecosystems, where wealth indicates
474 a vulnerable system, and human systems where wealth can help build adaptability.

475 The food system that feeds urban regions in the West has all three characteristics of a
476 vulnerable system. It is highly productive or biologically wealthy, non-diverse and tightly
477 connected. However, we clearly do not want to reduce the productivity of agricultural
478 regions, and, in many ways, this productivity depends on the agricultural system being
479 tightly connected and homogenous. Policy needs to be focused at maintaining the biological
480 wealth of modern agriculture while maintain diversity and limiting connectivity so that if a
481 disturbance does threaten food supplies in one region, the problem cannot spread and so that
482 urban consumers maintain a number of different avenues to obtain food. The benefit of using
483 this framework from landscape ecology is that it can reduce the number of variables under
484 consideration, which makes the remaining information more useful in developing a
485 planning tool. It is only a framework, however, not a predictive model, and as such makes no
486 attempt to anticipate when, where or what form a problem might take. Therefore, this
487 approach should be seen as one method to identify troublesome areas for careful study.

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