Crop genetic erosion: a review of 100 years of evidence, thoughts on future research, and an outline of steps needed to mitigate, stem, and reverse further losses

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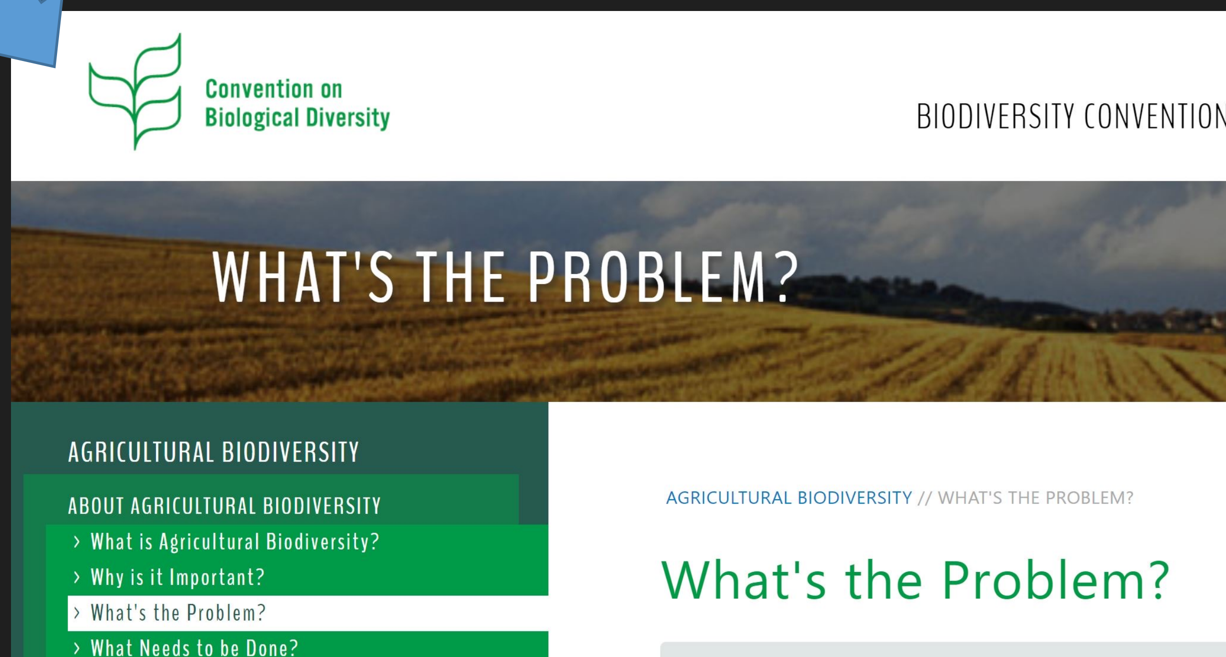
I. Introduction

Genetic diversity in crop species provides a reservoir of traits from which farmers can find, and plant breeders can develop, plant varieties best suited to local production conditions. Accessing this reservoir of crop genetic diversity will be especially important as climate change alters growing conditions for many farmers—making some areas hotter, or drier, or shifting growing seasons or the ranges of crop pests. **Yet agricultural biodiversity throughout the world experienced a sharp decline over the past century, with around 75 percent of crop genetic diversity lost.**[1]

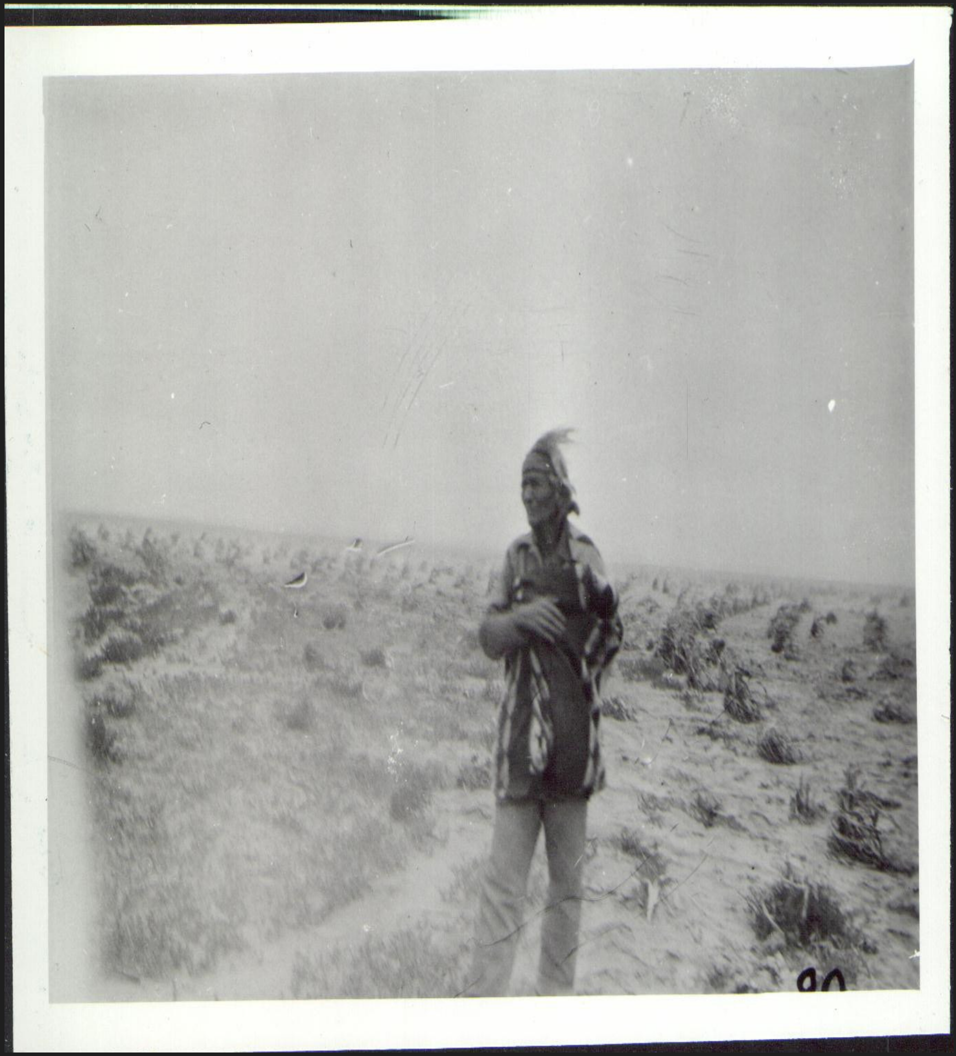
weedkiller. Companies patent the crops they develop so that no one else may sell or use them without permission.

Declining crop genetic diversity, combined with increasing patent protection over what genetic diversity remains, constrains farmers and plant breeders alike. Farmers have fewer options for planting, and plant breeders may lose access to the genetic diversity they need to create new varieties when much of that diversity is owned by agribusiness as intellectual property. Additionally,

“According to the FAO, it is estimated that about three-quarters of the genetic diversity found in agricultural crops has been lost over the last century, and this genetic erosion continues.”



https://www.vermontlaw.edu/sites/default/files/2020-01/Defensive-Publication-Guide.pdf
https://www.cbd.int/agro/whatstheproblem.shtml



Photos: Gary Nabhan

Definitions

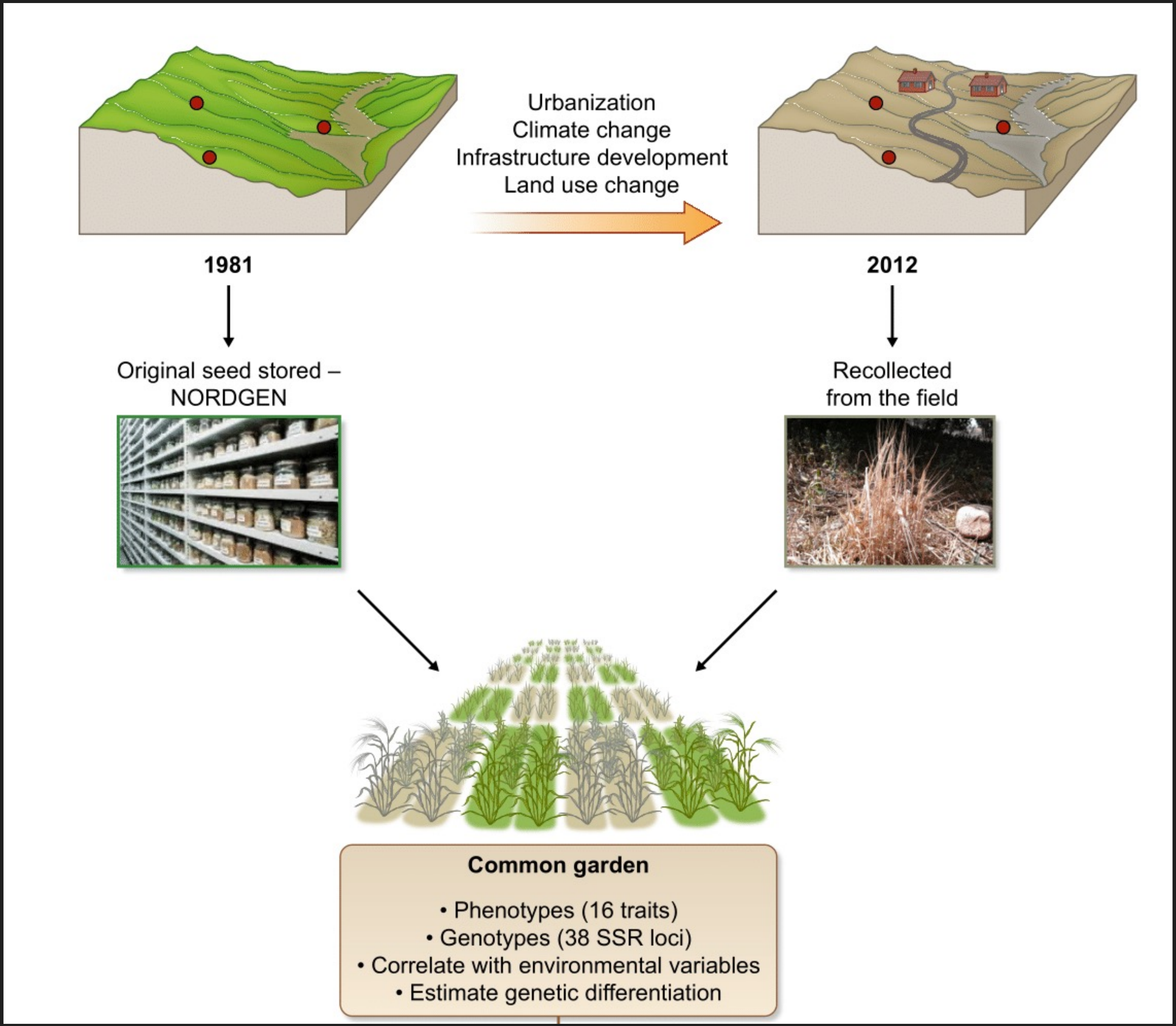
- **Crop diversity**: variation among crop species, their varieties, and/or individual plants' genotypes and phenotypes

- **Crop genetic erosion**: the loss of crop diversity in a given area over a given amount of time, typically measured by decline of species, variety, and/or within-variety variation

Scope

- All crops and their wild relatives
- All time periods
- All locations
- All geographic scales – global, regional, national, sub-national, community, farm, accession
- All taxonomic scales – species, varieties/populations, traits/genes/alleles
- All analytical methods – field observations, surveys/interviews, genetic, phenotypic, literature, modeling, etc.
- All measurement targets - absolute losses, changes in richness, changes in abundance/frequencies/evenness

Spectrum of direct - indirect comparisons



Khoury *et al.* (2021) Crop genetic erosion: understanding and responding to loss of crop diversity. Tansley review, *New Phytologist*. doi: 10.1111/nph.17733. Data from Thormann *et al.* (2017a, b).

Overview

- 288 total articles with evidence of change over time; 232 primary articles
- Published between 1939 - 2021
- 103 venues - *GRACE* (37), *TAG* (21), *Crop Science* (15), *Euphytica* (8); *PGR: Characterization and Utilization* (8), *PNAS* (7), *PLoS One* (7); 96 other journals/media with 5 or less articles
- Crops: Wheat (50), Maize (24), Rice (24), Barley (16), Sorghum (9), Potato (7), Oat (5); 38 other crops with 4 or less articles each; 44 additional articles with multicrop focus
- Study locations: Americas (N America [33], C America and Mexico [19], S America [14]), Europe (NW Europe [25], SW Europe [23]), Asia (S Asia [17], E Asia [14]), Africa (E Africa [22], W Africa [13]), Global (16), Pacific (3)
- Scale: Sub-country (106), Country (86), Region (24), Global (12), Community (4)
- Time period: 1900s-2000s (4000 BCE) to 1990s-2010s (2099). Median length of study period 40 yr.
- Taxonomic scale: Within-varietal (129), Varietal (120), Species (52)
- Analytical tool: Genetic (112), Social/field survey (89), Nomenclatural (42), Phenotypic (28), Pedigree (10), Modeling (4); 185 S; 47 M
- Study resource: Biological materials (124), Farmer knowledge (60), Published information (38), Field observations (33), Pedigree information (11), Remote data (6)

Crop diversity contexts

- Traditional crop landraces on farms
- Modern crop cultivars in agriculture
- Crop wild relatives (CWR) in their natural habitats
- Crop genetic resources held in conservation repositories (*ex situ* conservation)
- Crop diversity in food systems (human diets, food supplies, trade, etc.)

Photo: Wisconsin Historical Society

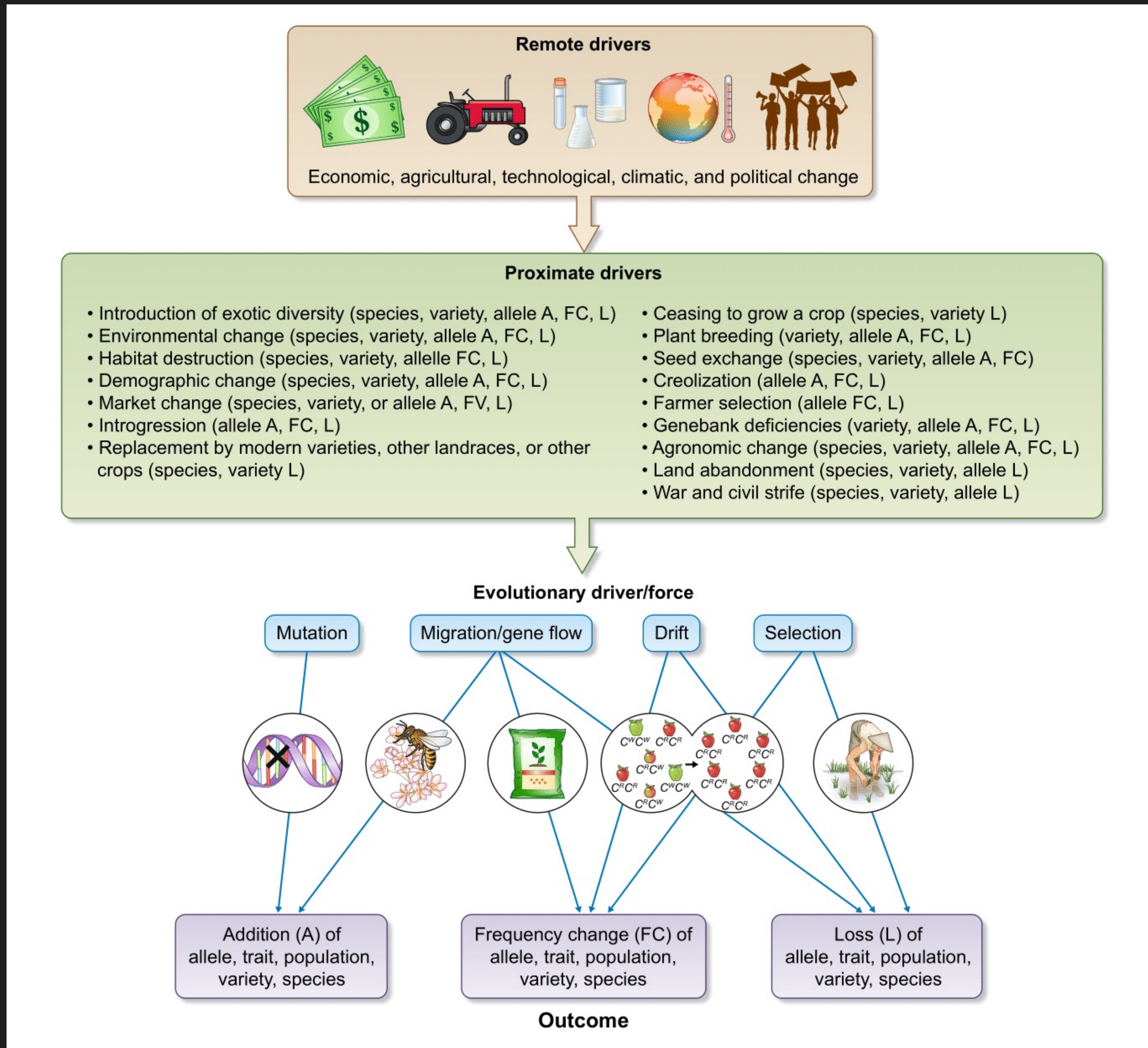
Traditional crop landraces on farms - overview

- 139 articles published between 1939 and 2021
- Maize (18), Wheat (16), Rice (14), Barley (9), Sorghum (8), Potato (5), Bean (4); 28 other crops with 2 or less articles each; 31 additional articles with multicrop focus
- Americas (C America and Mexico [18], S America [11], N America [9]), Africa (E Africa (20], W Africa [12], N Africa [6]), Asia (S Asia [11], W Asia [9], SE Asia [7]), Europe (SW Europe [13], NW Europe [8]), Global (10), Pacific (1)
- Sub-country (88), Country (28), Region (11), Global (8), Community (4)
- Varietal (100), Within-varietal (52), Species (42)
- Social/field survey (82), Genetic (41), Nomenclatural (33), Phenotypic (20)
- Farmer knowledge (60), Biological materials (52), Published information (28), Field observations (27)
- 1920s-2000s (4000 BCE) to 1990s-2010s (2099). Median length of study period 28 yr

Traditional crop landraces on farms - results

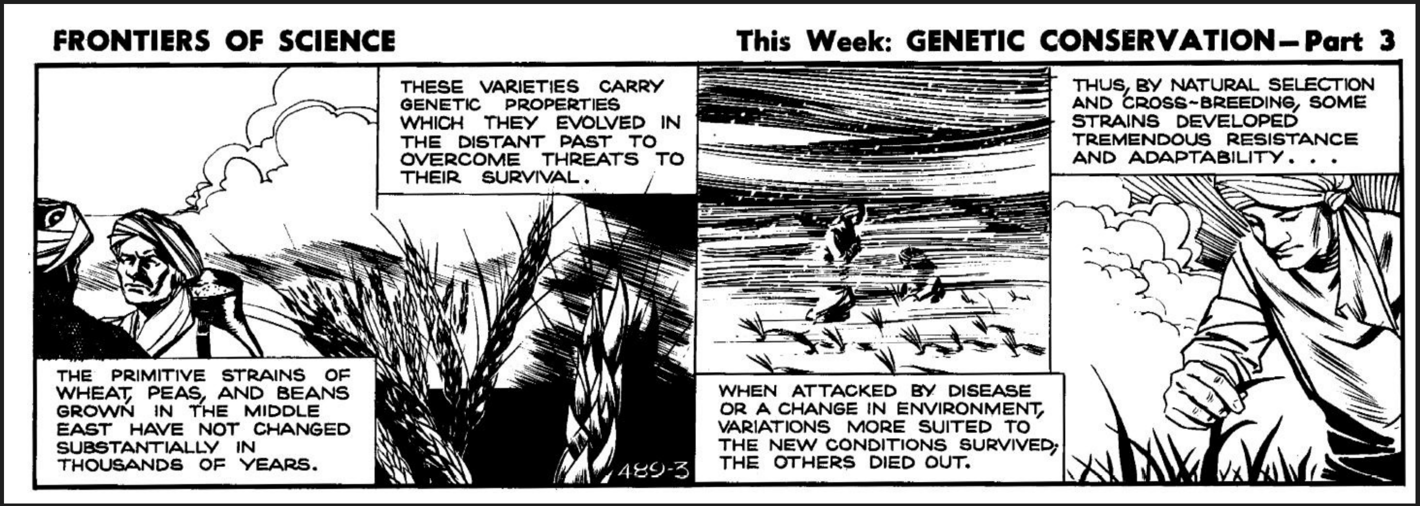
- 96.4% (134) articles documented change
- 86.3% (120) documented loss
- Complete disappearance of specific landraces and a few crop species, declines in richness, and losses of within-landrace variation. Also declines in the harvested area, or number of farmers/families/villages cultivating specific landraces.
- Reductions in differences between landrace populations – increasing homogeneity

Traditional crop landraces on farms - drivers



Khoury *et al.* (2021) Crop genetic erosion: understanding and responding to loss of crop diversity. Tansley review, *New Phytologist*. doi: 10.1111/nph.17733.

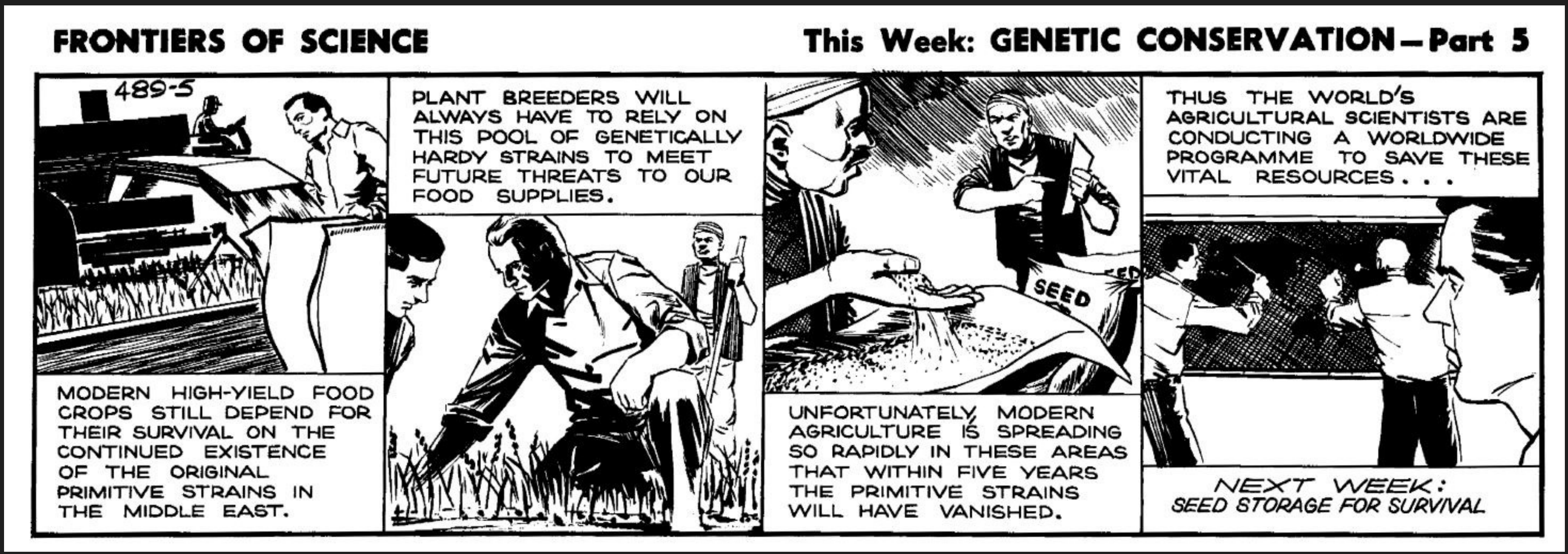
Traditional crop landraces on farms - caveats



- Interchange and turnover of landraces is widespread
- Non-cereal/commodity crops may not follow same pattern
- Loss of genotypes/populations doesn't necessarily imply overall decline
- Adoption of modern cultivars does not necessarily equate with landrace loss
- 33.8% (47) of articles documented maintenance of diversity; 23.7% (33) documented increases

Khoury *et al.* (2021) Crop genetic erosion: understanding and responding to loss of crop diversity. Tansley review, *New Phytologist*. doi: 10.1111/nph.17733. Figure from Butler *et al.* (1971).

Traditional crop landraces on farms - caveats



Khoury *et al.* (2021) Crop genetic erosion: understanding and responding to loss of crop diversity. Tansley review, *New Phytologist*. doi: 10.1111/nph.17733. Figure from Butler *et al.* (1971).

Photo: USDA, Preston Keres

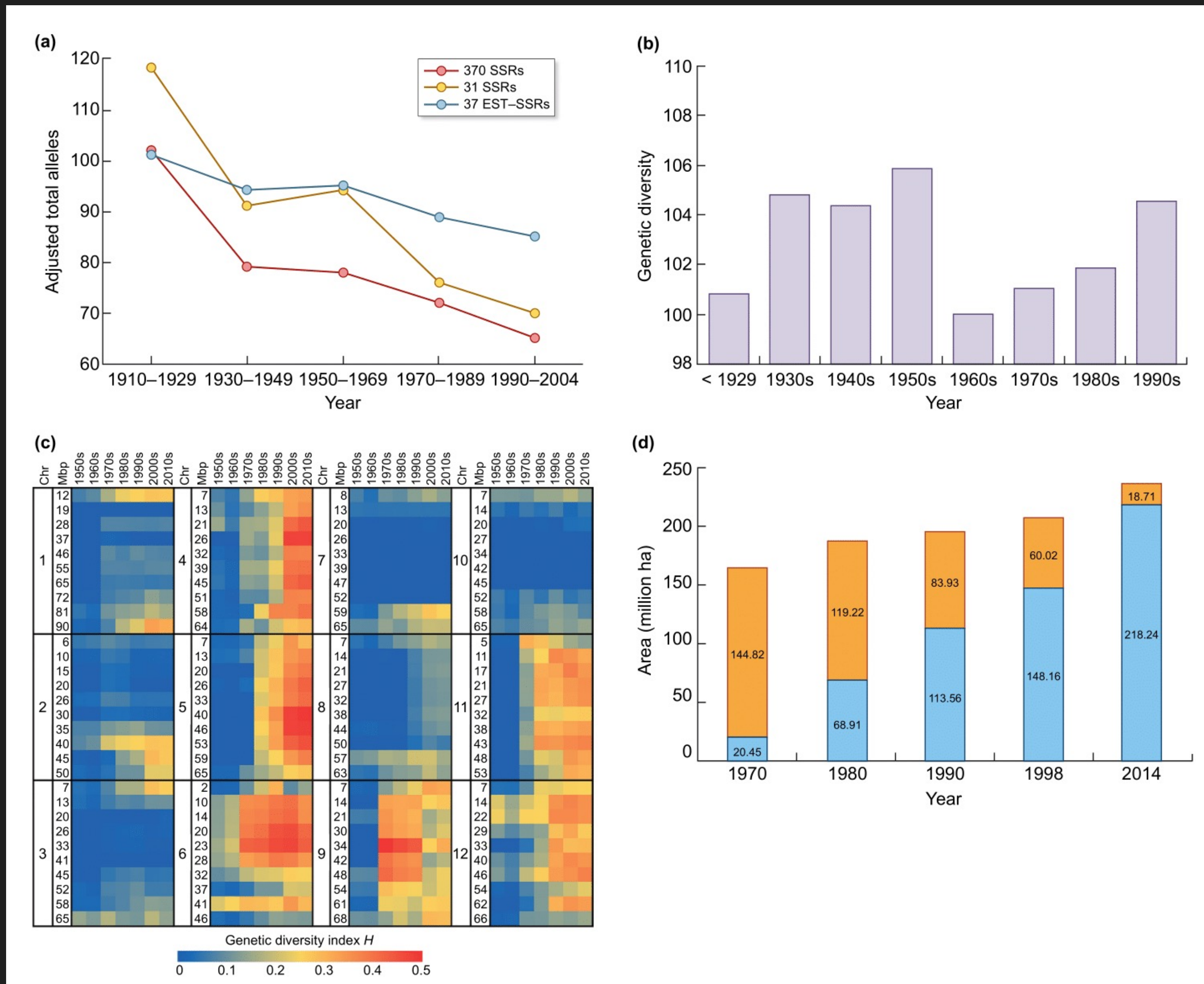
Modern crop cultivars in agriculture - overview

- 105 articles published between 1984 and 2021
- Wheat (40), Barley (8), Maize (8), Rice (8), Oat (4), Potato (3), Soybean (3); 14 other crops with 2 or less article each; 12 additional articles with multicrop focus
- Europe (NW Europe [21], SW Europe [13], NE Europe [10], SE Europe [7]), Americas (N America [26]), Asia (S Asia [10], E Asia [8]), Global (8), Africa (2), Pacific (2)
- Country (62), Sub-country (18), Region (17), Global (7), Community (1)
- Within-varietal (85), Varietal (34), Species (11)
- Genetic (75), Nomenclatural (13), Social/field survey (13), Pedigree (10), Phenotypic (8)
- Biological materials (77), Published information (16), Pedigree information (11), Farmer knowledge (9), Field observations (5)
- 1900s-1970s (1200) to 1990s-2000s (2014). Median length of study period 59 yr

Modern crop cultivars in agriculture - results

- 93.3% (98) articles documented change
- 67.6% (71) documented loss
- Increasing homogeneity in cultivars also documented
- 43.8% (46) of articles documented maintenance of diversity; 47.6% (50) documented increases

Modern crop cultivars in agriculture – results and caveats



Khoury *et al.* (2021) Crop genetic erosion: understanding and responding to loss of crop diversity. Tansley review, *New Phytologist*. doi: 10.1111/nph.17733. Figures from Fu & Dong (2015), van de Wouw *et al.* (2010), Schouten *et al.* (2019), and Gatto *et al.* 2021


Photo: Laura Marek

Crop wild relatives in their natural habitats - overview

- 33 articles published between 1988 and 2020
- CWR of Rice (4), Maize (3), Coffee (2), Barley (2); 8 other crops with 1 article each; 12 additional articles with multicrop focus
- Asia (E Asia [3], W Asia [3], SE Asia [2]), Americas (C America and Mexico [5], N America [3]), Africa (E Africa [6], W Africa [3], C Africa [2], S Africa [2]), Global (6), Europe (SW Europe [2])
- Sub-country (17), Country (6), Global (6), Region (4)
- Species (18), Within population (18), Population (16)
- Field survey (17), Genetic (13), Nomenclatural (8), Phenotypic (3), Predictive modeling (3)
- Biological materials (14), Field observations (11), Farmer knowledge (5), Published information (6), Remote data (3)
- 1950s-1990s (1927) to 2000s-2010s (2089). Median length of study period 17.5 yr

Crop wild relatives in their natural habitats - results

- 97% (32) articles documented change
- 90.9% (30) documented or predicted loss
- Increasing homogeneity in CWR also documented (increasing geneflow between CWR populations and with crops, due to habitat disturbance)
- 18.2% (6) of articles documented maintenance of diversity; 15.2% (5) documented increases
- Drivers: changes in land use, climate, agronomic practices (regarding wild relatives occurring in traditional agricultural fields), and environment

Photo: Neil Palmer/CIAT

Crop genetic resources held in repositories – overview

- 28 articles published between 1995 and 2021
- Rice (4), Wheat (4), Barley (3), Bean (3), Maize (3), Potato (2); 6 other crops with 1 article each; 3 additional articles with multicrop focus
- 23 articles focus on cultivated materials (23 on landraces, 7 on modern cultivars), 8 on crop wild relatives
- Americas (N America [4], C America and Mexico [3]), Europe (NW Europe [4], NE Europe [2]), Asia (E Asia [3], W Asia [2]), Africa (3), Global (3)
- Sub-country (16), Country (8), Global (3), Community (1)
- Within-varietal (23), Varietal (8), Species (3)
- Genetic (20), Phenotypic (8), Social/field survey (8), Nomenclatural (4)
- Biological materials (24), Published information (4)
- 1950s-1990s (1831) to 1990s-2010s (2017). Median length of study period 31 yr

Crop genetic resources held in repositories – results

- 100% (28) articles documented change
- 85.7% (24) documented loss
- 42.9% (12) of articles documented maintenance of diversity; 28.6% (8) documented increases
- Drivers: regeneration or multiplication activities, human error (unintentional introgression or mixing from other samples)

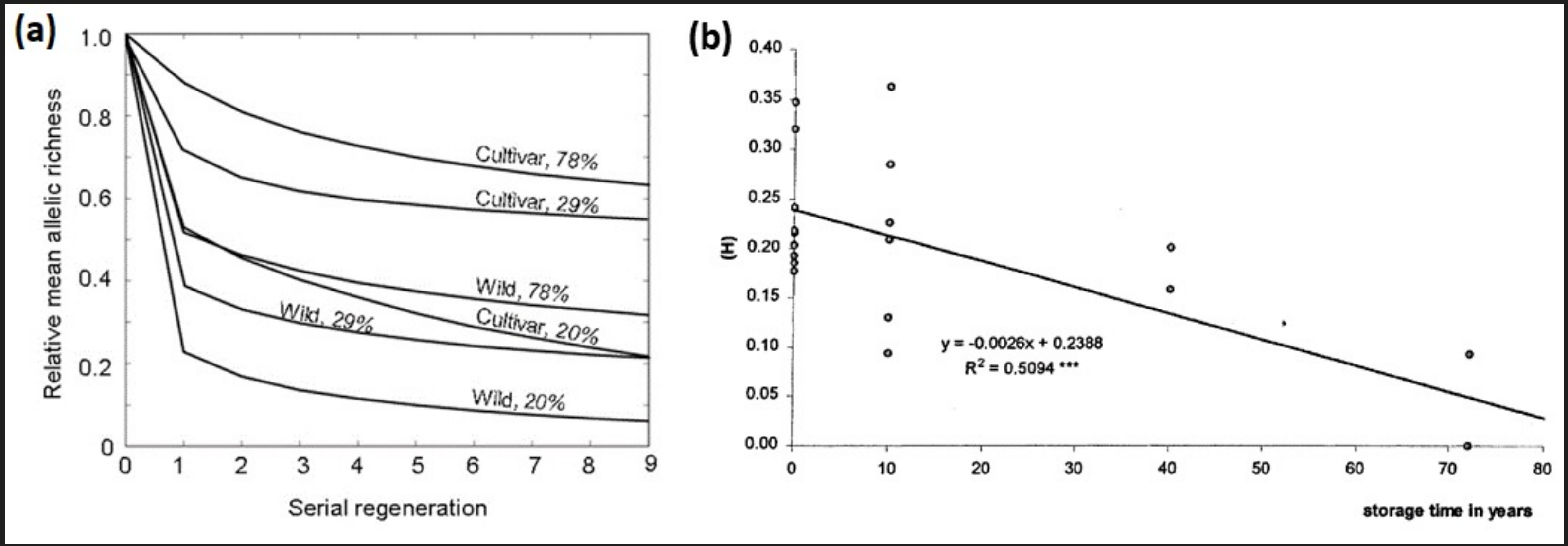


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Photo: Manon Koningstein

Breadth, complexity, and inclusiveness of research

- Study more crops and crop types, and their CWR
- Study more regions
- Study at landscape and larger scales; also study micro-scales
- Study other forms of agricultural diversity
- Widen engagement/participation

Breadth, complexity, and inclusiveness of research

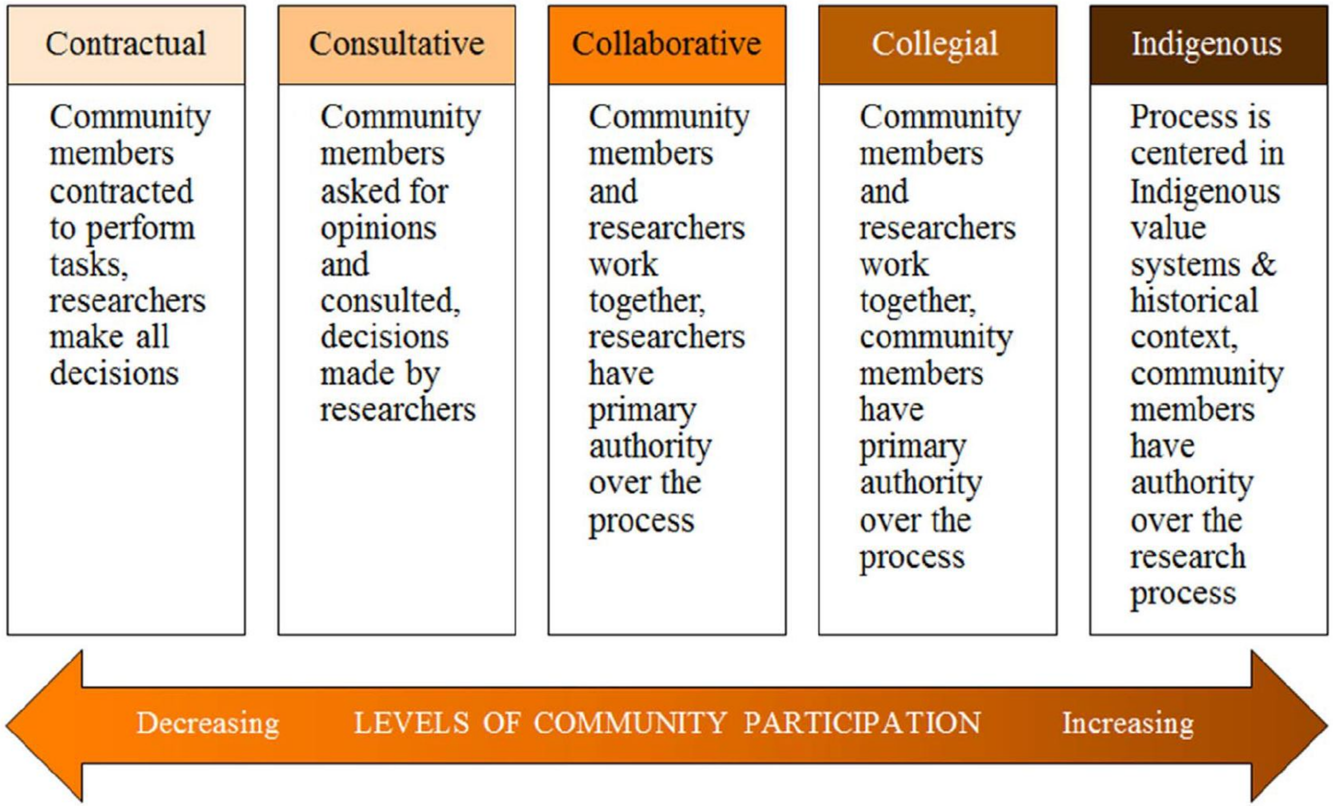


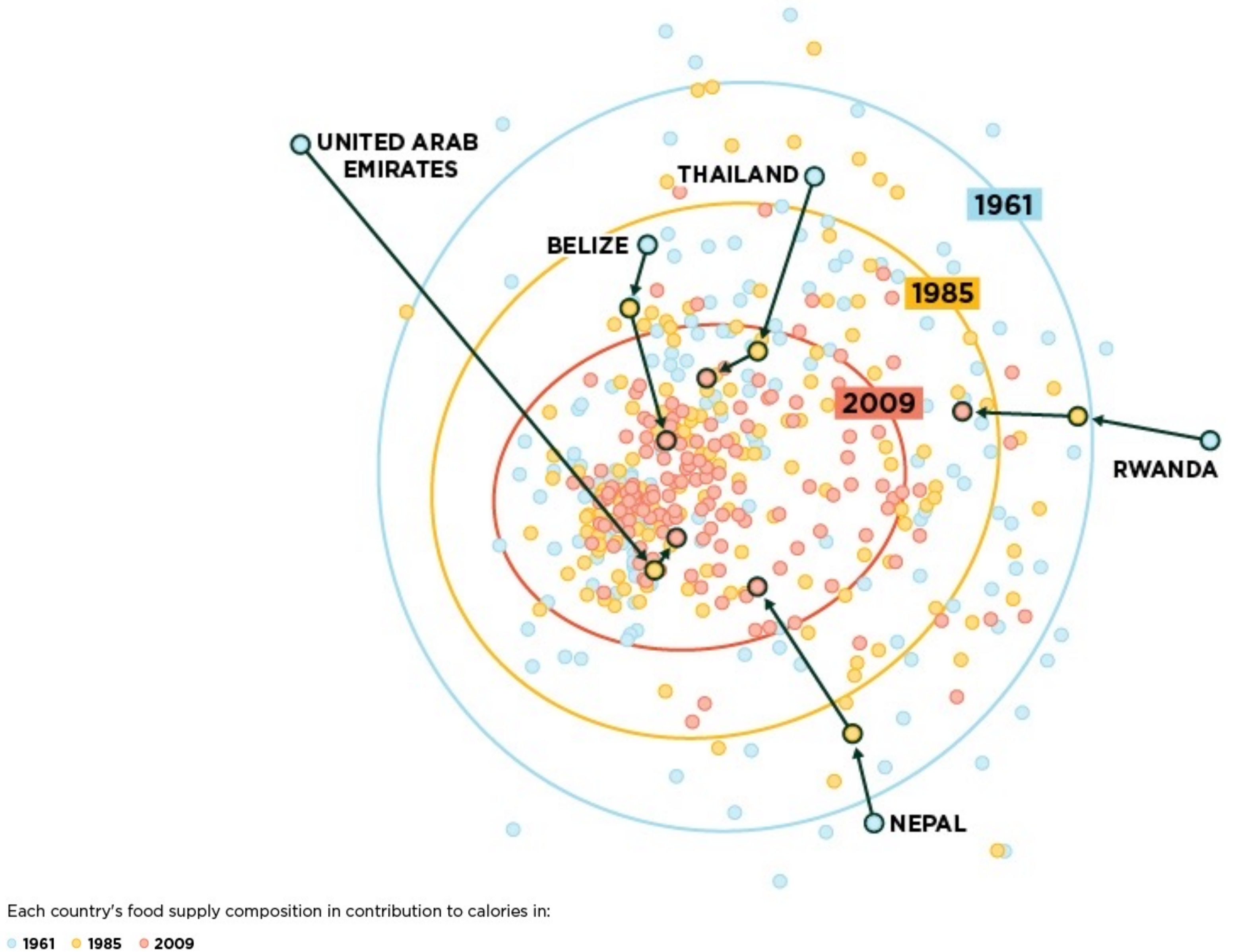
Figure 1. Scale for assessing levels of Indigenous community participation based on who has authority over the research process (adapted primarily from Biggs 1989, Johnson *et al* 2003).

David-Chavez & Gavin (2018) A global assessment of Indigenous community engagement in climate research. *Environmental Research Letters* 13: 123005.

Robustness of the methods and underlying theory

- Acknowledge inherent limitations
- Develop more sophisticated direct comparative methods
- Focus on permanent/significant change
- Focus on agronomically and societally significant traits
- Investigate increasing homogeneity and its implications
- Integrate temporal and spatial change

Relevance of crop genetic erosion to society



Khoury *et al.* (2014) *PNAS* 111(11): 4001-4006

Conservation implications of crop genetic erosion

Photo: Native Seeds/SEARCH

Conclusions

"Since the beginning of this century about 75 percent of the genetic diversity among agricultural crops has been lost" (FAO 1993).

- 79.3% of articles documented evidence of loss of crop diversity
- 37.1% documented maintenance, and 29.7% increases/appearance of new diversity
- Diversity of landraces in farmers' fields and of crop wild relatives in their natural habitats continue to decline, although substantial landrace diversity continues to be cultivated
- Ups and downs for modern cultivars
- Increasing homogeneity documented among cultivars, landraces, wild relatives, and national food supplies
- Change in the diversity of genetic resources held *ex situ* is common

Photo: Neil Palmer

Ex situ conservation

- Continue efforts to safeguard crop diversity *ex situ*
- Bolster capacities of and funding for *ex situ* repositories
- Improve/complete safety duplication
- Improve accessibility of collections
- Embrace "non-conventional" *ex situ* repositories
- Improve access and benefit sharing policies


Photo: K. Williams

In situ/on-farm conservation

- Enhance *in situ* conservation for continued evolution and for agroecosystem resilience and local autonomy
- Develop stronger *in situ* conservation approaches, with focus on farmer-led efforts. Embrace change and focus on the conditions and processes that foster diversity
- On-farm conservation interventions warranted where significant loss occurring and where there is demand
- For CWR, develop inventories, management plans, raise awareness with land managers


COLORADO GROWN
SAKATA FARMS
Bob Sakata
1945
Brighton, Colorado
Farming sweet corn, broccoli, cabbage and onions
4
seasonal
weekly specials
spaghetti sauce
italian foods
6
rice & dry beans
salad dressing
pickles & olives
8
COLORADO GROWN
COLORADO GROWN
certified organic
Low price!
Kiln Dried Yams
Low price! 1.29

Formal seed systems

- Advocate and agitate for diversified bases of commodity crops
- Re-invest in public breeding
- Continue to develop farmer participatory breeding
- Critically assess trends (industry consolidation, IPR, technologies) and then act to minimize negative impacts on diversity

BIODIVERSIDAD

desarrollo y bienestar

¡Conservémosla!

International Plant Genetic Resources Institute

IPGRI

NOMBRE COMUN	NOMBRE CIENTIFICO	ORIGEN	NOMBRE COMUN	NOMBRE CIENTIFICO	ORIGEN	NOMBRE COMUN	NOMBRE CIENTIFICO	ORIGEN
1 PIÑA	ANANAS COMOSUS	PARAGUAY Y SUR DE BRASIL	30 UVAS NEGRAS	VITIS VINIFERA	ASIA MENOR	59 LIMA	CITRUS LIMETTA	SURESTE DE ASIA
2 PAPAYA	CARICA PAPAYA	CENTROAMERICA	31 BABACO	CARICA X PENTAGONA	ALTOS ANDES	60 PITANGA	EUGENIA UNIFLORA	SUR DE BRASIL
3 SANDIA	CITRULLUS VULGARIS	AFRICA DEL SUR	32 BANANO	MUSA AAA	INDOMALASIA	61 GUAYABA ARGELINA	PSIDIUM CATTLEIANUM	SUR DE BRASIL
4 TANGELO MINEOLA	C. RETICULATA X C. PARADISI	USA	33 LIMON CASTILLA	CITRUS AURANTIFOLIA	SUROESTE DE ASIA	62 CANISTEL	POUTERIA CAMPECHIANA	DE MEXICO A PANAMA
5 LIMON VARIEGADO	CITRUSS AURANTIUM "MARGINATA"	MALASIA	34 MELON	SICANA ODORIFERA	BRASIL	63 MANDARINA ONECO	CITRUS RETICULATA	DE CHINA A NORESTE DE INDIA
6 MANGO YURIMA	MANGUIFERA INDICA	INDOMALASIA	35 LIMON TAHITI	CITRUS LATIFOLIA	SUROESTE DE ASIA	64 MANDARINA ARRAYANA	CITRUS RETICULATA	DE CHINA A NORESTE DE INDIA
7 GUANABANA	ANNONA MURICATA	NORTE DE SURAMERICA	36 TAMARILLO	CYPHOMANDRA BETACEAE	ALTOS ANDES	65 NISPERO COSTEÑO	MANILKARA ZAPOTA	DE MEXICO A COSTA RICA
8 CACAO	THEOBROMA CACAO	AMERICA TROPICAL	37 GRANADA	PUNICA GRANATUM	ASIA MENOR	66 BREVAS	FICUS CARICA	ASIA MENOR
9 POMELO	CITRUS GRANDIS	SURESTE DE ASIA	38 ANON CIMARRON	ROLLINIA MUCOSA	NORTE DE SURAMERICA	67 PERA DE MALACA	EUGENIA MALACCENSIS	MALASIA
10 GUAMA COPERA	INGA HETEROPTERA	TROPICO AMERICANO	39 MARACUYA	PASSIFLORA EDULIS	BRASIL	68 GUAYABA CORONILLA	PSIDIUM FRIEDRICHSTHALIANUM	CENTROAMERICA Y COLOMBIA
11 CARAMBOLO	AVERRHOA CARAMBOLA	TROPICO DE ASIA	40 ZAPOTE	MATISIA SAPOTA	NORTE DE SURAMERICA	69 UVA DEL AMAZONAS	POUROUMA CECROPIAEFOLIA	OESTE DE LA AMAZONIA
12 UVA VERDE	VITIS VINIFERA	ASIA MENOR	41 BALAZO	MONSTERA DELICIOSA	CENTROAMERICA	70 CALAMUNDY	CITRUS MITIS	SURESTE DE ASIA
13 BOROJO	BOROJOA PATINOI	PACIFICO COLOMBIANO	42 CHIRIMOYA	ANNONA CHERIMOLIA	NORTE DE SURAMERICA	71 ICACO	CHRYSOBALANUS ICACO	AMERICA Y AFRICA TROPICAL
14 CASTAÑO DEL CHOCO	PACHIRA AQUATICA	TROPICO AMERICANO	43 OLLA DE MONO	LECYTHIS OLLARIA	AMAZONIA O VALLE MAGDALENA	72 CIRUELA ROJA	SPONDIAS PURPUREA	CENTROAMERICA
15 CURUBA LARGA	PASSIFLORA MOLLISIMA	ALTOS ANDES	44 ALGARROBO	HYMENAEA COURBARIL	TROPICO AMERICANO	73 TORONJA ROJA	CITRUS PARADISI	SURESTE DE ASIA
16 CHONTADURO	BACTRIS GASIPAES	AMAZONAS	45 NARANJA WASHINGTON	CITRUS SINENSIS	SURESTE DE ASIA	74 ACEROLA	MALPIGHIA EMARGINATA	ANTILLAS
17 COCO	COCOS NUCIFERA	ASIA O AMERICA	46 LULO	SOLANUM QUITOENSE	ALTOS ANDES	75 SESO VEGETAL	BLIGHIA SAPIDA	COSTA DE GUINEA
18 MANGO LAOS	MANGUIFERA INDICA	INDOMALASIA	47 AGUACATE COLLINS REED	PERSEA AMERICANA	DE MEXICO A COLOMBIA	76 NISPERO DEL JAPON	ERIOBOTRYA JAPONICA	SUR DE CHINA
19 PACO	GRIAS CAULIFLORA	PACIFICO COLOMBIA	48 BADEA	PASSIFLORA QUADRANGULARIS	NORTE DE SURAMERICA	77 FRAMBUESA	RUBUS ROSAEFOLIUS	INDIA
20 GRANADILLA	PASSIFLORA LIGULARIS	ALTOS ANDES	49 MELON CANTALUPE	CUCUMIS MELO	AFRICA ORIENTAL	78 GROSELLAS	PHYLLANTHUS ACIDUS	ASIA
21 PAPAYUELA	CARICA CUNDINAMARCENSIS	ALTOS ANDES	50 UCHUVA	PHYSALIS PERUVIANA	ALTOS ANDES	79 MORAS	RUBUS GLAUCUS	DE MEXICO A ECUADOR
22 PANA	ARTOCARPUS ALTILIS	DE NUEVA GUINEA A MALASIA	51 PITAYA AMARILLA	CEREUS TRIANGULARIS	CENTROAMERICA	80 CEREZA DE CEILAN	DOVYALIS HEBECARPA	SRILANKA
23 COROZO	AIPHANES CARYOTAEFOLIA	AMERICA TROPICAL	52 PITAYA ROJA	CEREUS TRIANGULARIS	CENTROAMERICA	81 MACADAMIA	MACADAMIA INTEGRIFOLIA	NORESTE DE AUSTRALIA
24 CHULUPA	PASSIFLORA MALIFORMIS	SURAMERICA Y ANTILLAS	53 MANGO SENSACION	MANGUIFERA INDICA	INDOMALASIA	82 TAMARINDO	TAMARINDUS INDICA	AFRICA
25 MAMEY	MAMMEA AMERICANA	NORTE DE SUR AMERICA	54 HIGO	OPUNTIA FICUS INDICA	MEXICO	83 GUAYABA	PSIDIUM GUAJAVA	AMERICA TROPICAL
26 ZAPOTE COSTEÑO	POUTERIA SAPOTA	DE MEXICO A COSTA RICA	55 MADROÑO	RHEEDIA MADRUNNO	CENTRO Y SURAMERICA	84 MARAÑON	AÑACARDIUM OCCIDENTALE	NORESTE BRASIL
27 TOMATE DE ARBOL	CYPHOMANDRA BETACEA	ALTOS ANDES	56 ANON LISO	ANNONA RETICULATA	CENTROAMERICA	85 CAMU-CAMU	MYRCIARIA DUBIA	AMAZONIA
28 GENIPA	GENIPA AMERICANA	CUBA Y R. DOMINICANA	57 TANGELO ORLANDO	C. RETICULATA X C. PARADISI	USA	86 FRESA	FRAGARIA CHILOENSIS	SUR DE CHILE
29 CAÑAFISTULA	CASSIA GRANDIS	BRASIL	58 CITRON	CITRUS MEDICA	SUROESTE DE ASIA	87 MAMONCILLO	MELICOCCA BIJUGĄ	LITORAL CARIBE

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Tel.:(57-2) 445-0000 Ext. 648; Fax: (57-2) 445-0273; Email: Ciat-ipgri @ cgnet. com

Societal change

- (Re)organize global agriculture, and food systems, and even the human societies they nourish, to become diversity-supportive processes
- (Re)integrate species, varietal, and genetic diversity into agricultural systems, both temporally and spatially
- (Re)establish local autonomy and markets supporting the processes that foster the ongoing evolution of crop diversity
- Integrate the importance of, and threats to, crop diversity, in educational curricula and outreach

Thank you!

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https://doi.org/10.1111/nph.17733

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