

Chapter 1

The Potassium Cycle and Its Relationship to Recommendation Development



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Abstract Nutrient recommendation frameworks are underpinned by scientific understanding of how nutrients cycle within timespans relevant to management decision-making. A trusted potassium (K) recommendation is comprehensive enough in its components to represent important differences in biophysical and socioeconomic contexts but simple and transparent enough for logical, practical use. Here we examine a novel six soil-pool representation of the K cycle and explore the extent to which existing recommendation frameworks represent key plant, soil, input, and loss pools and the flux processes among these pools. Past limitations identified include inconsistent use of terminology, misperceptions of the universal importance and broad application of a single soil testing diagnostic, and insufficient correlation/calibration research to robustly characterize the probability and magnitude of crop response to fertilizer additions across agroecozones. Important opportunities to advance K fertility science range from developing a better understanding of the mode of action of diagnostics through use in multivariate field trials to the use of mechanistic models and systematic reviews to rigorously synthesize disparate field studies and identify knowledge gaps and/or novel targets for diagnostic development. Finally, advancing evidence-based K management requires better use of legacy and newly collected data and harnessing emerging data science tools and e-infrastructure to expand global collaborations and accelerate innovation.

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1.1 Overview of the Potassium Cycle

Nutrient recommendation frameworks are underpinned by scientific understanding of how nutrients cycle within timespans relevant to management decision-making. The cyclic nature of K transfers and transformations in crop production can be shown by a diagram depicting pools of K in the soil-plant system and the fluxes of K between those pools within a given volume of soil for a specified period of time (Fig. 1.1). Time scales typically reference a crop within a season or a sequence of crops within a relatively short period of time (2–4 years) for which a single or small suite of interrelated management decisions will be made. The horizontal spatial extent may range from an individual plant to an entire farm enterprise but traditionally has emphasized the “field scale,” reflecting a farmer’s predetermined management unit. The vertical spatial boundaries typically range from the top of the crop canopy down into the soil to the depth of crop rooting. Therefore, the spatial and temporal extents of interest include all system components that are intrinsic to the soil and the site as well as those that are influenced by management and crop development. Together, these components directly influence crop productivity.

Pools in the K cycle (Fig. 1.1) are categorized as inputs (pool 1), outputs (pools 2–5), plant pools within the cycle boundaries (pools 6–7), and those within the soil (pools 8–13).

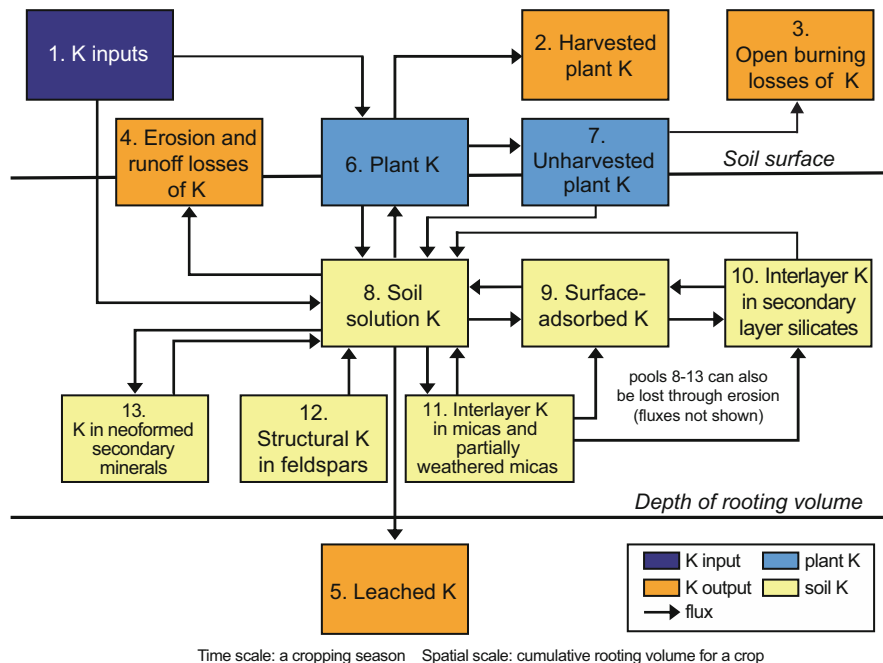


Fig. 1.1 The K cycle. Pools are denoted by rectangles and are quantities of K in one or more types of locations. Fluxes are denoted by arrows and are movements of K from one pool to another. This cycle depicts six pools of soil K (referenced herein as the six soil-pool model)

(pools 8–13). These pools are examined in depth throughout this book; their abbreviations relevant to this chapter are provided in Table 1.1. The pools are as follows:

Pool 1. K inputs is the total quantity of K originating outside a given volume of soil that moves into that volume. Inputs include organic and inorganic fertilizer additions (K_{Fert} , Table 1.1); K in crop residues brought onto the field from other areas; K in precipitation; K in irrigation water; K transported to the soil volume via runoff and erosion; K brought in as seeds, cuttings, or transplants; and atmospheric deposition (Chap. 2). This pool is the sum of all of these inputs. Inputs may occur directly to the soil or, as is the case with foliar fertilizer applications, directly to the plant.

Pool 2. Harvested plant K is the quantity of K in plant material removed from a given area (K_{Harv}). Such losses occur as the K in the desired plant products is removed from the field—products such as grains, forages, fruits, vegetables, nuts, ornamentals, and fibers (Chap. 3).

Pool 3. Open burning losses of K are the total quantity of K lost from the unenclosed combustion of materials. When crop residues left in the field (pool 7) are burned, K in soot and ash is lost if they move offsite (Chap. 3).

Pool 4. Erosion and runoff losses of K group three losses of K: surface runoff, subsurface runoff, and erosion (Chap. 3). **Surface runoff K** is K^+ in water moving laterally over the soil surface in the direction of the slope. **Subsurface runoff K** is K^+ in water that infiltrates the soil surface to shallow depths and then moves laterally in the direction of the slope. **Erosion loss of K** (K_{Erode}) is K lost from the lateral or upward movement of soil particles out of a given volume of soil. Although not depicted by arrows in the diagram, erosion and runoff losses include both soil solution K (pool 8) and K in the soil solids (pools 9–13).

Pool 5. Leached K (in soil) is the quantity of K displaced below the rooting depth by water percolating down the soil profile (K_{Leach}) (Chap. 3). Potassium dissolved in the soil solution (K_{Soln}) is subject to leaching, shown by the single flux arrow connecting pool 8 to pool 5. Although not depicted in the diagram, K can also be lost with clay colloids translocating to subsurface horizons.

Pool 6. Plant K is the total quantity of K accumulated in the plant (K_{Plant} or K_{TotPlant} as discussed below). Total accumulation considers both aboveground organs, such as stems, leaves, flowers, and fruit, and belowground organs, such as roots, rhizomes, and corms. Nearly all of plant K is taken up by roots from the soil solution, shown by the arrow from pool 8 to pool 6 (Chap. 4). **Influx** is the movement of K from outside to within a tissue, in this case from the soil solution into the roots (Barber 1995). Small quantities of K may also move out of plant roots back into the soil solution. **Efflux** is the movement of K from within to outside a tissue (Barber 1995; Cakmak and Horst 1991). Efflux is denoted by the arrow drawn from pool 6 to pool 8. Plants differ in their efficiencies of K uptake and utilization (Chap. 5). Potassium can also enter the plant via leaf penetration, shown by the arrow from pool 1 to pool 6 (Marschner 2012). Potassium deposited on leaf surfaces by foliar fertilization, throughfall (Eaton et al. 1973), and

Table 1.1 Definitions of abbreviations as used in the text. Comments are included to provide additional clarity and context

Term	Abbreviation	Definition
Plant K	K_{Plant}	The K content in all plant biomass, usually reported on a dry matter basis, that is newly taken up within the growth cycle/season (the new plant nutritional need). It is measured at the point of maximum accumulation, ideally representing optimal growth and realizing maximum economic yields but without luxury consumption. Note, in annuals, K_{Plant} is often only assessed in aboveground tissues only
Total plant K	K_{TotPlant}	The total quantity of K that a plant/crop requires within the growth cycle/season, measured at the point of maximum accumulation representing optimal growth and realizing maximum economic yields. For annuals, $K_{\text{TotPlant}} = K_{\text{Plant}}$
Total organ K	K_{OrganTot}	The total quantity required by a specific organ pool of a plant/crop (leaves, stem/stalk, ear/fruitletting body, root system, etc.)
Internally translocated K	K_{Trans}	Portion of K_{PlantTot} or K_{OrganTot} that is met by internal K cycling and translocation within a crop/plant
Plant-available indigenous K	K_{Soil}	The quantity of native K supplied by the soil without new K additions that is newly taken up by a plant/crop within a growth cycle/season
Harvested K	K_{Harv}	The quantity of K in plant material removed from a given area by crop harvest
Unharvested K	K_{UnHarv}	The amount of K returned to the soil in unharvested residues after the growing season/cycle
K concentration in harvested tissue(s)	K_{AveConc}	Average value of the K concentration in all harvested tissues that can be used to estimate K_{Harv} from yield mass
Solution K	K_{Soln}	The quantity of K in the soil solution, i.e., the soil pool from which plant/crop roots take up K
Solution soil test K	STK_{Soln}	A quick assay of K_{soln} that may be used in conjunction with quick assays of other soil pools to measure flux
Surface-adsorbed K	K_{Surf}	The quantity of K associated with negatively charged sites on soil organic matter, planar surfaces of phyllosilicate minerals, and surfaces of iron and aluminum oxides
Exchangeable K	K_{Exch}	The K extracted from a sample of soil via cation exchange using a solution of a specified composition (e.g., NH_4^+ or Na^+ salts) under a specific set of conditions. It is typically assumed that release occurs primarily from K_{Surf} , although release can also come from K in readily accessible interlayer positions of soil minerals. To provide an agronomic interpretation, K_{Exch} must be correlated to crop uptake and/or yield (see STK_{Exch})
Useable fraction of exchangeable K	E_{Exch}	Efficiency or fraction of K_{Exch} that is taken up by the root system of the crop/plant during the growing season/cycle
Exchangeable soil test K	STK_{Exch}	The total quantity of K in a soil sample that is released by a routine exchanging test protocol that has been

(continued)

Table 1.1 (continued)

Term	Abbreviation	Definition
		correlated with crop K uptake and/or yield (e.g., $STK_{\text{Exch}} = K_{\text{Exch}} \times E_{\text{Exch}}$), typically also inclusive of K_{Soiln}
Quantity of K in solid-phase pool j	K_j	The total quantity of K in pool “ j ,” where j corresponds to K in secondary layer silicates, micas and partially weathered micas, structural K in feldspars, or K in neoformed secondary minerals (pools 10–13, Fig. 1.1)
Useable K fraction in pool j	E_j	The efficiency or fraction of pool K_j that is taken up by the plant root
Plant-available nonexchangeable K	K_{NonExch}	Quantity of K in secondary layer silicates, micas, feldspars, and neoformed secondary minerals (K_j) accessed by plant/crop roots during a growth season or cycle (e.g., $K_{\text{NonExch}} = \sum_{j=\text{pool } 10}^{j=\text{pool } 13} K_j \times E_j$, Fig. 1.1)
Nonexchangeable soil test K	STK_{NonExch}	A chemical assay of potential seasonal contributions to K_{Soiln} from soil pools 9–13 in Fig. 1.1. (Note: In any routine laboratory test, the protocol will also assess K_{Exch} contributions)
Erosion K losses	K_{Erode}	The quantity of K lost from the movement of soil particles out of a given volume of soil
K lost to leaching	K_{Leach}	The quantity of K displaced below the rooting depth by water percolating within the soil profile
Fixed K	K_{Fixed}	The quantity of K that has moved to interlayer positions in phyllosilicate minerals and has subsequently become unavailable to plants during the growing season/cycle
Precipitated K	K_{Precip}	Soil K that becomes unavailable to the crop/plant during the growing season/cycle following precipitation as neoformed secondary minerals
Lost K	K_{Lost}	The sum of K losses via all loss pathways (K_{Erode} , K_{Leach} , K_{Fixed} , and K_{Precip}) of soil K or K added either as inorganic/organic fertilizer or as unharvested residues (K_{UnHarv})
Fertilizer K	K_{Fert} or K_{FertX}	The input requirement for K fertilizer to meet the portion of plant K demand (K_{Plant}) not supplied by the soil while accounting for expected loss processes (K_{Fert}) or a specific input of fertilizer at rate “X” (K_{FertX})
Efficiency of fertilizer K uptake	E_{Fert} or E_{KAdded}	The efficiency of any single fertilizer application (E_{Fert}) or net K addition, including the sum of K_{Fert} and K_{UnHarv} (E_{KAdded}), that reflects the non-indigenous (soil) portion of system K that is taken up by the plant within the coming growth season/cycle. The efficiency factor adjusts the new K requirement upward from the net plant nutrition need ($K_{\text{Plant}} - K_{\text{Soil}}$) and accounts for losses in plant-available K (K_{Lost}) following K addition
K uptake with rate “X”	$K_{\text{Soil} + \text{X}}$	Total plant K uptake at a specific fertilizer rate “X”
K recovery efficiency	RE_K	The apparent recovery efficiency for a specific fertilizer rate “X” (e.g., $RE_K = (K_{\text{Soil} + \text{X}} - K_{\text{Soil}})/K_{\text{FertX}}$), which is an approximation of E_{KAdded}

atmospheric deposition (Chap. 2) contribute secondarily to plant K via this pathway.

Pool 7. Unharvested plant K (Chap. 6) is *the quantity of plant K returned to the soil volume (K_{UnHarv})*. This return is normally associated with K leached from dead plant material such as pruned branches and leaves in orchards, chaff from machine harvest of grain crops, terminated cover crops, and plant residues left from previous crops. **Leached K** is *the quantity of K removed from plant tissues by water including rain and dew*. Leaching of K can be more rapid from senescing tissues where membranes and cell walls are damaged prior to moisture exposure (Burke et al. 2017). Although also considered leaching, guttation is another process that may lead to loss of K. **Guttation** is *an exudation of xylem sap from leaves due to root pressure* (Taiz et al. 2018). Guttation loss occurs from living tissue.

Pool 8. Soil solution K (Chap. 7) is *the quantity of K dissolved in the aqueous liquid phase of the soil (K_{Soln})* (Soil Science Glossary Terms Committee 2008). It is present as the cation K^+ . Plants take up K^+ only from this pool, denoted by the flux arrow from pool 8 to pool 6. Many soil pools (pools 9–13) contribute K to K_{Soln} .

Pool 9. Surface-adsorbed K is *the quantity of K associated with negatively charged sites on soil organic matter, planar surfaces of phyllosilicate minerals, and surfaces of iron and aluminum oxides (K_{Surf})* (Chap. 7). Surface-adsorbed K enters the soil solution the most readily and is therefore considered the most plant-available of the soil K pools. As shown by the bidirectional fluxes between pools 8 and 9, K_{Soln} can become K_{Surf} and vice versa.

Pool 10. Interlayer K in secondary layer silicates is *the quantity of K bound between layers of phyllosilicate minerals that are weathering products of primary minerals* (Chap. 7). Secondary layer silicates are formed primarily by transformations of micas and feldspars. The strength of the bonds that K^+ forms in interlayers varies by mineral; therefore, not all interlayer K has the same degree of plant availability. Potassium may move from interlayers to surface sites (arrow from pool 10 to pool 9) or directly to K_{Soln} (arrow from pool 10 to pool 8). Additionally, K_{Surf} may move to the interlayers (arrow from pool 9 to pool 10).

Pool 11. Interlayer K in micas and partially weathered micas (Chap. 7) is *the quantity of K bound between layers of primary mica minerals that are in various stages of chemical and physical breakdown*. Important K-containing micas are biotite and muscovite. Micas do not release plant-available K until chemical or physical forces act upon them. As phyllosilicate micas weather, the edges of their sheets open as hydrated cations replace the dehydrated K^+ originally in the structures. Potassium from these edges may go into the K_{Soln} (arrow from pool 11 to pool 8) or to K_{Surf} (arrow from pool 11 to pool 9). The loss of K near the edges of mica crystals is concomitant with the loss of internal negative charge in the crystal and leads to the formation of secondary minerals. Interlayer K in micas can become interlayer K in secondary layer silicates (arrow from pool 11 to pool 10).

Pool 12. Structural K in feldspars (Chap. 7) is *the quantity of K in structures of tectosilicate minerals, mainly feldspars, and feldspathoids*. The K in these minerals is not bound as strongly as the other elements in the structures. At exposed surfaces, dissolution of the structures can allow other cations in the soil solution to exchange for K^+ , moving K^+ into the solution (arrow from pool 12 to pool 8).

Pool 13. Neofomed K minerals are *newly formed minerals created from the reaction of soil solution K with other soil solution ions* (Chap. 7). An example is taranakite, a mineral formed by the reaction of K with phosphorus fertilizer compounds under acidic, saturated solution conditions (Lindsay et al. 1962). Potassium in neofomed secondary minerals can be both a source of K to K_{Soln} as plants deplete K_{Soln} (arrow from pool 13 to pool 8) and a sink for K as newly added K is precipitated out of K_{Soln} (arrow from pool 8 to pool 13).

1.2 Philosophy of a Potassium Recommendation

Cash et al. (2003) stated that to be effective, scientific information has to be credible, salient, and legitimate. Applied to a K recommendation, it is credible when it is scientifically adequate and based on sufficient evidence. It is salient when it addresses the needs of the decision-makers. It is legitimate when it is unbiased and respects stakeholders' values and beliefs. Both scientists and practitioners alike want a recommendation to be "accurate," in that it provides realistic estimates of costs and benefits, with associated levels of confidence, for a given K management option and a given set of conditions that are specific to the user. From the scientific perspective, accuracy is achieved when (1) the individual components that make up the recommendation (i.e., modification for crop, soil type, agroecozone, etc.) are consistent with relevant scientific theory and (2) research has been conducted under a sufficient number of representative conditions and environments that the statistical precision and accuracy of the recommendation can be explicitly given for its inference space. For practitioners, accuracy requires that the recommendation be credible in that it makes sense out of what is observed and that the components themselves can be observed, explained, and understood. Additionally, practitioners desire a recommendation that is customizable to individual contexts (management, environment, whole-farm profitability, etc.) and is not only focused on the cost and benefits associated with a single crop's response to a single nutrient. Finally, practitioners expect recommendations to be reasonably successful in predicting crop production outcomes.

Philosophically, this suggests a three-legged stool model for building a recommendation, where simultaneous consideration is given to (1) the crop-soil K cycle, (2) the ancillary or secondary biophysical factors that can influence the crop-soil K cycle but are often the subject of separate recommendations, and (3) socioeconomic factors that encompass farmer short- and long-term objectives, goals, and preferences (Fig. 1.2). Thus, there is more to a recommendation than understanding the crop- and soil-specific attributes of the K cycle, and all three legs must be subjected

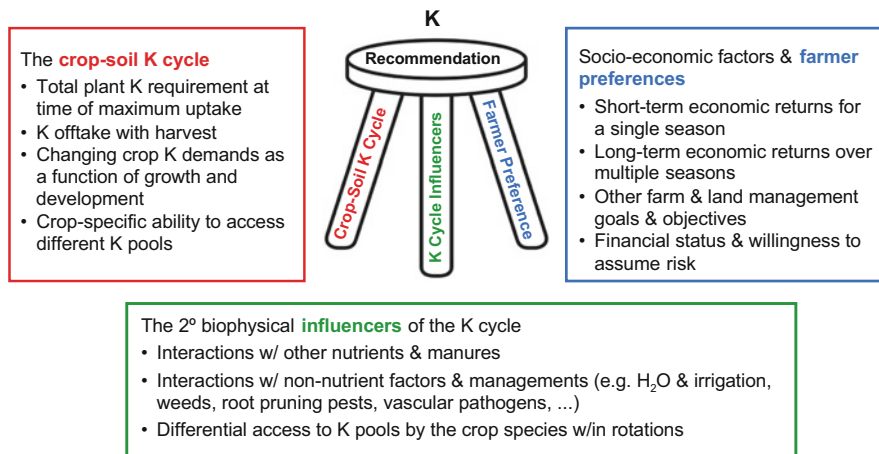


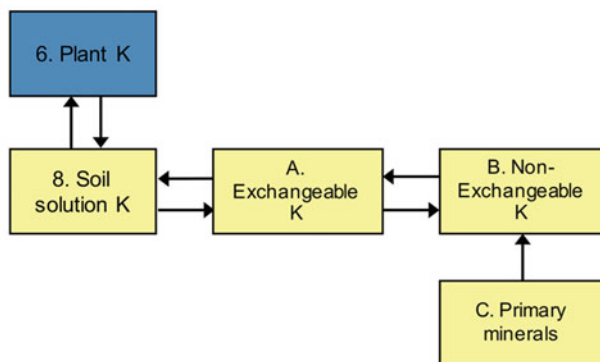
Fig 1.2 A “three-legged stool” conceptualization of the essential considerations of a credible, salient, and legitimate K recommendation

to rigorous analysis. The remainder of this chapter will focus primarily on the crop-soil K cycle and its biophysical regulators. These are the legs of the stool that have been the subject of most agronomic research conducted to develop K recommendations.

1.3 Challenges with Common Potassium Recommendation Terminology

In most soil fertility references and management guides (e.g., Havlin et al. 2014), soil K has been represented as residing in four distinct pools (Fig 1.3a). The K_{Soln} and exchangeable K (K_{Exch} , Table 1.1) pools have long been considered the major in-season source of nutrients to plants and crops and the major foci of research to develop soil testing protocols. The remaining two soil pools in traditional K cycle diagrams were the structural K in primary minerals and the interlayer K in secondary clay minerals. However, as discussed in the remainder of this chapter and in Chap. 7, this traditional four soil-pool model and the accompanying terminology have created confusion in understanding the plant-soil K cycle and its use as a foundation to recommendations. The four soil-pool model uses terminology that confounds the mechanisms of extraction protocols with the actual source pools (e.g., K_{Exch} for the quantity of K extracted via cation exchange versus nonexchangeable K (K_{NonExch} , Table 1.1 and pool B, Fig. 1.3a) for any additional K that may be assessed by using other extractants). Additionally, it lumps together micas and feldspars, does not consider neoformed minerals, and suggests that primary minerals are not important

a. Conventional four soil-pool model



b. Simplified two soil-pool model

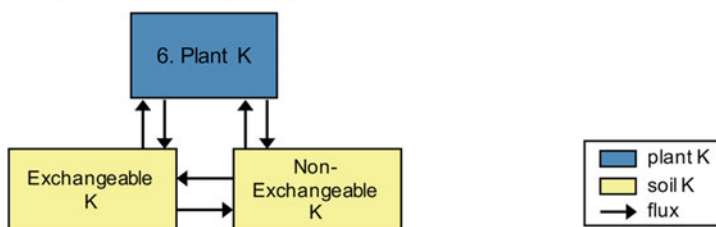


Fig. 1.3 Two simplified K cycles depicting only the relationships among soil K and plant K pools. Other pools have been omitted for simplicity. Pools are denoted by rectangles and are quantities of K in one or more types of locations. Fluxes are denoted by arrows and are movements of K from one pool to another. Pools 6 and 8 retain the numbering from Fig. 1.1. The upper cycle (a) is the conventional four soil-pool model. The lower two soil-pool cycle (b) is a simplified model that conceptualizes plant-available K as coming from pools measured by a soil test that extracts K with cation exchange (exchangeable and soil solution K) and not measured by such a soil test (nonexchangeable K)

contributors to plant nutrition within typical management timelines (Fig. 1.1, pools 11, 12, and 13).

The consensus among contemporary K researchers is that inconsistency in terminology creates challenges in communicating among scientists and in achieving a recommendation that is understandable and credible to the practitioner. The six soil-pool model (Fig. 1.1) is intended to be more explicit in clarifying potential contributors to K_{Soln} during a growing season and potential sinks for K added as fertilizers, manures, and returned residues and to result in more defensible recommendations. Although more complex, it is expected to alleviate the array of confusions generated by the four soil-pool model and thereby facilitate a more informed understanding of soil assays by mode of action and use of the K cycle to improve research that supports K recommendations.

Terms associated with the four soil-pool model known to be differentially used and prone to creating confusion in trying to communicate the science underpinning a recommendation, along with their clarifying definitions used in this book, include:

- The use of “exchangeable” or “replaceable” to characterize K that is removed with a cation exchange assay that is often assumed to represent just surface-adsorbed K (Fig. 1.1, pool 9). To clarify this term, Chap. 7 defines **exchangeable K** as *the K extracted from a sample of soil via cation exchange using a solution of a specified composition under a specific set of conditions*. As Chap. 8 explains, exchangeable K, when measured by ammonium cations in the soil test extractant, is surface-adsorbed K as well as K in readily accessible interlayer positions of soil minerals. Other exchanging cations (e.g., Na^+ , Ba^{2+} , or Ca^{2+}) or extraction conditions may not extract the same amount of K from a soil sample as ammonium does.
- Various uses of the term “fix” (i.e., fixed K, K fixation, a K-fixing soil) to characterize movement of K into interlayer sites of clay minerals, rendering the ion less accessible to the soil solution and therefore less plant-available (Fig. 1.1, movement of K from pools 8 or 9 into pools 10 or 11). The term has also been used to characterize a soil factor expected to reduce the efficiency of a fertilizer K application. Chapter 7 defines **potassium fixation** as *hydrated K^+ ions moving to interlayer positions in phyllosilicate minerals and then dehydrating as the mineral layers contract. In this position, the K^+ is unavailable to plants*.
- “Nonexchangeable” and “exchangeable” terms are sometimes used to classify the relative ease with which K^+ on the cation exchange complex of a soil can be replaced by other cations (ammonium (NH_4^+), magnesium (Mg^{2+}), and calcium (Ca^{2+})) in the soil solution. But the terms are often used synonymously with either fixation terms or analytical protocols such as nitric acid-extractable K versus ammonium acetate K, respectively (McLean and Watson 1985). Chapter 7 defines nonexchangeable K as soil K that is not measured by soil tests that rely on exchange or displacement of K by another cation. In this chapter we use the abbreviation K_{NonExch} to represent the plant-available portion of nonexchangeable K that is accessed by plant/crop roots within seasons or over a few years and might, thus, be a target of a measurement to support a K recommendation.
- Various terms characterizing “available” K (i.e., bioavailable, plant-available, etc.). These terms have been used to describe both the concentration and quantity of K extracted by a soil test protocol (that has been found to be correlated with plant uptake) and the proportion of a crop’s K requirement that can be seasonally accessed from the indigenous soil K supply by crop roots. In this and the following chapters, plant-available and bioavailable K are used interchangeably.
- Other terms characterizing outcomes or states of processes such as K “holding capacity” and aspects of efficiency (i.e., uptake, recovery, physiological, agronomic, etc.). These terms are generally assumed to be quantitative, but the mathematical representation can vary in important ways among the users of the term(s). Chapter 3 defines **K holding capacity** as *the maximum quantity of K that can be retained by a given volume of soil*. Chapters 5 and 11 define several commonly used metrics of K efficiency.

The examples above point to efforts by other authors in this book to clarify terms.

1.4 Considerations for Recommendations Derived from the Mass Balance Approach to the Potassium Cycle

In principle, a fertilizer recommendation derived from a plant-soil nutrient cycle such as shown in Fig. 1.1 could focus on all or a subset of the pools and fluxes identified, with pool and/or flux choice reflecting the desired degree of fidelity of the recommendation in space and time. In practice, many nutrient recommendation frameworks use a mass balance approach that considers the predominant pools of nutrient supply and demand and represents complex flux processes as fractions of pools that can reasonably be considered as interacting within the context of a crop season or short sequence of crops for which a management intervention is planned. Thus, the dimension of real time is effectively removed as a direct variable. In the literature, this approach has been most explicitly described for N and directly applied to N management (Stanford 1973; Morris et al. 2018), but the approach is generic and can be applied to any nutrient. In comparing the basic information required for optimizing both yields and fertilizer recovery as identified for N by Stanford (1973), commonalities for K include:

1. For plants or crops that attain the yield expected for a given environment, the internal requirement for K newly taken up from the soil (plant K or K_{Plant} ; Fig. 1.1, pool 6) assessed at the point of maximum accumulation and inclusive of all plant tissues including roots (Fig. 1.4).
2. The amount of K that a plant or crop can obtain from the plant-available indigenous soil K supply (K_{Soil}).
3. The understanding that the quantity of fertilizer applied (K_{Fert}) must be higher than the difference between K_{Plant} and K_{Soil} to reflect the reality that recovery efficiency of fertilizer will most likely be reduced from 100% by a variety of practical management considerations and common soil and other environmental conditions.

For K, the basic Stanford equation is

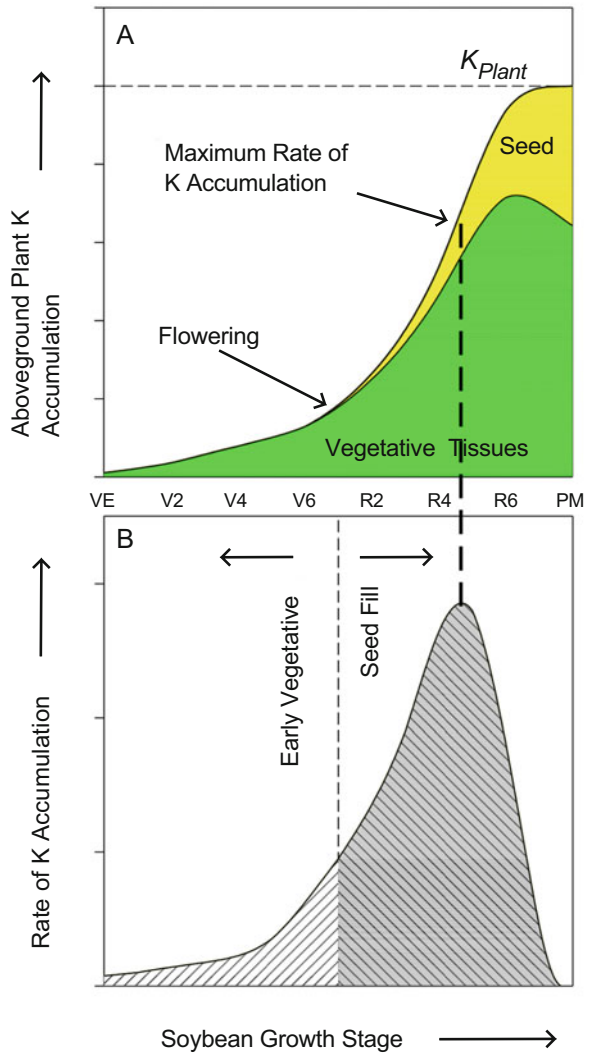
$$K_{\text{Fert}} = (K_{\text{Plant}} - K_{\text{Soil}})/E_{\text{Fert}} \quad (1.1)$$

Or by rearranging

$$K_{\text{Fert}} \times E_{\text{Fert}} = K_{\text{Plant}} - K_{\text{Soil}} \quad (1.2)$$

where E_{Fert} is the efficiency with which the K fertilizer is maintained as available for uptake by the plant or crop (i.e., if 75% is taken up within the growing season, then $E_{\text{Fert}} = 0.75$).

Fig. 1.4 (a) Total quantity of aboveground K accumulation and (b) the corresponding rate of accumulation by soybean (*Glycine max* (L.) Merr.) shown as a function of crop growth stage from vegetation emergence (VE) through physiological maturity (PM). Generalized curves are derived from Fernández et al. (2009)



1.4.1 Exploring and Characterizing K_{Plant} : Understood and Easily Assessed?

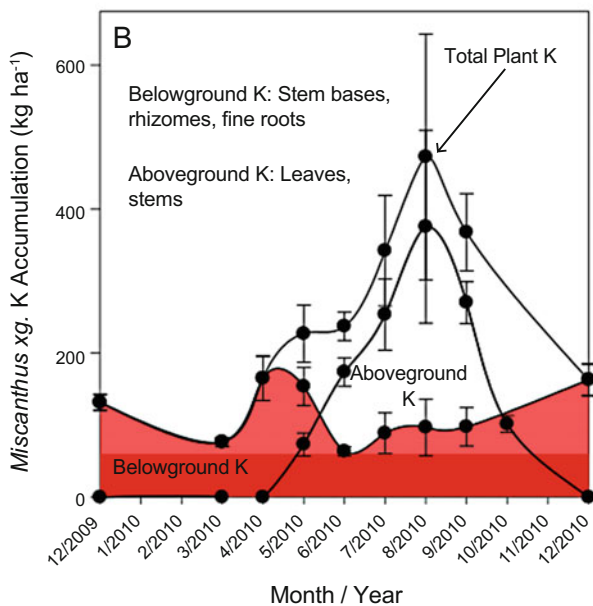
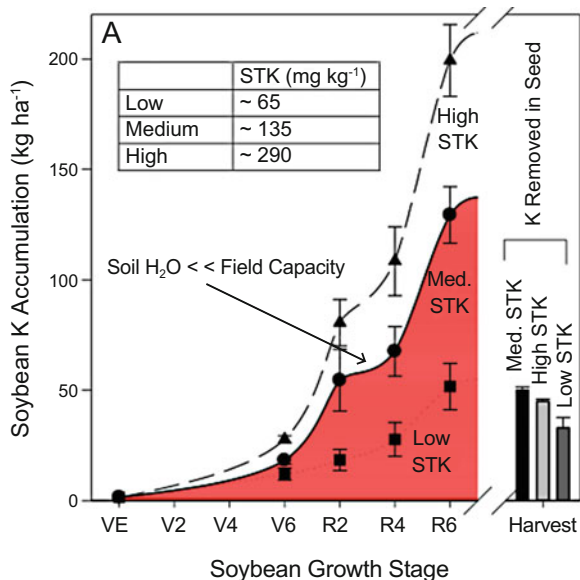
Potassium in plants performs an important array of functions, ranging from enzyme activation to its outstanding role in plant-water relations that drives everything from cell extension to the functioning of stomates and control of leaf gas exchange (Marschner 2012). Indeed, it is the wide diversity of functions as well as the high

quantities of K required by plants along with an apparent lack of toxicity effect at high tissue K concentrations that make plant K requirement particularly difficult to determine. When grown in soil with abundant K supply, luxury consumption of K in vegetative tissues and fleshy fruits can occur. Thus, identifying robust, species-specific values for K_{Plant} requires rate studies conducted in representative environments where results clearly delineate K_{Plant} at K sufficiency versus K excess conditions.

At sufficient but not excessive soil K supply, plant uptake in annual crops is roughly sigmoidal, with peak accumulation in aboveground tissue occurring at or before physiological maturity (Fig. 1.4a) and often well before actual harvest when some senescence of vegetative tissues has typically already occurred. For example, both Fernández et al. (2009) and Gaspar et al. (2017) document the relatively low level of K accumulation occurring during vegetative growth of soybean (*Glycine max* (L.) Merr.), followed by large increases in aboveground K during reproductive growth. In determinate annuals, this pattern may be shifted such that much of the uptake occurs prior to reproduction (e.g., maize; Ciampitti et al. 2013; Wu et al. 2014). The Fernandez et al. work (2008, 2009) also documents both the influence of soil moisture on temporal patterns of K accumulation and the importance of K rate studies to accurately determine K_{Plant} (Fig. 1.5a). In this example, rainfed soybean experienced a pause in K accumulation during seed development that corresponded with a 10-day period with <5 mm rainfall. During this time, gravimetric soil moisture content fell to <0.15 g g⁻¹ in the surface (0–20 cm) soil, well below field capacity (25 g g⁻¹). Further, soybean grown on high-testing soils, with 290 mg K kg⁻¹ in the top 10 cm of the profile, accumulated >50% more K_{Plant} by R6 than did soybean grown on medium-testing soils (135 mg K kg⁻¹), although yields and K removal in seed were the same on the high- and medium-testing soils.

In annuals, K_{Plant} , the plant's K requirement for new uptake from the soil for optimal growth throughout the growing season, is essentially the same as the total quantity of K in plant tissue (roots plus shoots, K_{TotPlant}). It is important to note that, in practice, most of the characterizations of K_{Plant} for annual grain, seed, and forage crops reflect measurements made on aboveground tissues (e.g., Fernández et al. 2009; Gaspar et al. 2017) with an assumption that belowground K in fibrous and taprooted root systems is relatively minor in comparison to quantities required by aboveground tissues. Although reports of root K contents are sparse and values are prone to variation due to experimental artifacts, Barber (1995) suggested that, in general, concentrations of K in roots are similar to that in shoots. If true, shoot K content and biomass shoot-to-root (S:R) ratios can be used to estimate root K. Studies of dry matter partitioning are also sparse but report that K in annual root systems may range from much less than 10 to over 20% of K_{Plant} . Amos and Walters (2006) integrated results from 45 studies on maize root biomass and identified anthesis as the point of maximum root biomass (31 g plant⁻¹) and a mean S:R dry weight ratio of 6:3 at physiological maturity, but variation among studies was pronounced. These authors also reported that several field studies had S:

Fig. 1.5 Potassium accumulation in (a) soybean (*Glycine max* (L.) Merr.) and (b) *Miscanthus* × *giganteus* (*Miscanthus* × *giganteus* J. M. Greef, Deuter ex Hodk., Renvoize). Error bars indicate the standard deviation (a) and error (b) of the mean. All aboveground tissues of soybean were pooled from plots with above optimal (high), optimal (medium), and deficient (low) K fertility status (modified from Fernández et al. 2009). *Miscanthus* data were collected over two sequential growing seasons from K-sufficient plots. (modified from Burks 2013)



Rs of <5 at maturity. In contrast, a recent field study of maize hybrids from the 1950s to the present day reports S:Rs of approximately 10 and 25 at tasseling and maturity, respectively (Ning et al. 2014). Amos and Walters (2006) noted an array of factors from genetic and environmental to sampling method artifacts can influence S:

Rs. Studies on soybean and wheat S:Rs at or near maturity are also variable (e.g., soybean 5.3 (Mayaki et al. 1976) and 11 (Brown and Scott 1984); wheat 5+ (Hocking and Meyer 1991) and 13 (van Vuuren et al. 1997)).

For crops with large underground storage organs that are the harvestable yield, the storage organs are generally included in K_{Plant} determination although fine roots are not (e.g., potato (*Solanum tuberosum* L.), sugar beet (*Beta vulgaris* L.), and other vegetables (Greenwood et al. 1980)). For perennial crops and trees, the K that a plant must newly acquire from soil for a given growing season (K_{Plant}) is different from total plant K accumulation (K_{PlantTot}). In perennial crops, total plant K accumulation includes both new K uptake (K_{Plant}) and K that is internally recycled from storage organs within a production cycle (K_{Trans}). To find K_{Plant} , the internally recycled K must be subtracted from total K accumulation, according to Eq. (1.3):

$$K_{\text{Plant}} = (K_{\text{PlantTot}} - K_{\text{Trans}}) \quad (1.3)$$

For *Miscanthus × giganteus* (*Miscanthus × giganteus* J. M. Greef, Deuter ex Hodk., Renvoize), a high-biomass grass that can be used for cellulosic bioenergy production, Burks (2013) found that root reserves (primarily in rhizomes) could account for 58% of the 175 kg K ha⁻¹ required for the first 2 months of shoot growth (Fig 1.5b, April–May). However, despite continued large accumulations of K in leaves and stems, K root reserves were partially replenished during the remaining summer months suggesting new uptake of soil K from June to August contributed to both above- and belowground K status. Additional important points about K_{Plant} illustrated by this study include (1) the high degree of variation (large standard error values) in K requirement of vegetative tissues and (2) the challenges of using time series snapshots to fully characterize K_{Plant} from the perspective of organ- or tissue-level mass balances. In theory, a more nuanced expression of K_{Plant} could capture the sum of the specific demands of n different organs or tissues where

$$K_{\text{Plant}} = \sum_{i=1}^n (K_{\text{OrganTot}_i} - K_{\text{Trans}_i}) \quad (1.4)$$

and K_{OrganTot_i} is the specific K requirement of every “ith” organ and K_{Trans_i} represents the portion of K received by the “ith” organ from any plant part that can temporarily store K. In practice, sequential mass balance measurements such as those made by Burks (2013) cannot easily distinguish on an organ basis whether accumulating K comes from new uptake or internal translocation. Thus, expanding Eq. (1.3) to Eq. (1.4) to represent internal K allocation at an organ level would likely do little to improve estimates of K_{Plant} when the purpose is to identify the general requirement of a plant or crop for new K uptake from soil for a specific season or cropping cycle.

Two additional plant K fractions are relevant to a mass balance approach to developing a fertilizer rate recommendation: the K removed with the harvested grain or organ (K_{Harv}) and the K in any plant residues that are returned to the soil (K_{UnHarv}),

discussed below with K_{Soil}). In recommendation systems that seek to raise K_{Soil} to sufficiency (e.g., $K_{\text{Soil}} = K_{\text{Plant}}$) and maintain it at this level, K_{Harv} is used to directly estimate K_{Fert} for applications to soils at K sufficiency or above (e.g., Vitosh et al. 1995). Historically, it has often been assumed that the fraction of K_{Plant} that is in the harvestable yield is constant and therefore the yield mass can be used as a proxy measure for K_{Plant} . For grain crops, seed K contents are highly conserved, and, thus, grain yields once adjusted to a standardized moisture contents can be used as a robust proxy measure of K removal in grain crops, provided crops are K sufficient (e.g., Brouder and Volenec 2008). In contrast, when the economic yields are vegetative tissues or fleshy fruits, harvested dry weights provide much less precise estimates of K_{Harv} (e.g., *Miscanthus* (Fig. 1.4b), Burks 2013; switchgrass (*Panicum virgatum* L.), Woodson et al. 2013)). For annual grains, low and highly variable harvest indices (HI) for K (K content of grain divided by K_{Plant}) limit the use of simple back calculations of K_{Plant} where

$$K_{\text{Plant}} = f(\text{Grain Yield}) \quad (1.5)$$

For N, the presumption of this relationship coupled with additional, simplistic assumptions about proportionality between the optimum fertilizer rate and plant N requirement led the Stanford (1973) model to be dubbed a yield-based approach to fertilizer recommendations. However, recent, rigorous analyses of the Stanford model have highlighted the pitfalls of reducing a mass balance understanding of a nutrient cycle to a recommendation largely derived from estimation of attainable yields or yield goals. Morris et al. (2018) note that, while logical to farmers, yield goal recommendations for N are limited by uncertainties in predicting realistic yields, relationships between uptake and yield, soil N supply, and important interactions among genetics, management, and environment. For K, the early emergence of soil testing as a tool for K management shifted the focus of historic recommendations away from yield goals as a major driver of K_{Fert} calculation. However, as K recommendations are revisited, agronomists should be mindful that similar uncertainties can be expected to plague such an overly reductionist approach to deriving a recommendation for K_{Fert} from the K cycle (discussed further below in Sect. 1.4.4.1).

1.4.2 Exploring and Characterizing K_{Soil} : Was Bray Right?

In his original report on a sodium acetate-nitric acid procedure for K in soils, Bray (1932) commented that the amount of replaceable K (easily exchangeable surface-adsorbed K, K_{Surf} (pool 9, Fig. 1.1)) in soils was generally considered to be a source of K to the soil solution and therefore available for plant growth. Although he noted other factors potentially influencing soil K that is “given up to the soil solution” (e.g., base cation exchange capacity), Bray identified replaceable K as the most important. This assumption remains the foundation for most K recommendations that involve

soil testing. Indeed, much of the subsequent research conducted in the intervening decades has focused on relating simple chemical tests characterizing the quantities of K released from solid phases by an exchanging or displacing cation (K_{Exch} ; common exchanging cations are sodium (Na^+) and NH_4^+) to fertilizer requirements (Bray 1944; Chap. 8). This approach results conceptually in a two soil-pool model (Fig 1.3b) and the associated common misperception that

$$K_{\text{Soil}} \cong K_{\text{Surf}} \cong K_{\text{Exch}} \quad (1.6)$$

where K_{Exch} is converted from a concentration measured by the chemical test to a mass of nutrient per unit land area by multiplying it by the approximate mass of a furrow slice of soil. In the USA, historic tabular recommendations often used the furrow slice conversion (mass of soil to depth of 20 cm (8 in)) interchangeably with a measured concentration (e.g., Vitosh et al. 1995). However, in reality, plant roots may not access all K in the furrow slice, and they may also access K from deeper in the soil, reflecting root distribution patterns (Chap. 8). Traditionally, recommended assays for K_{Exch} have followed extensive field work to identify good correlations with crop response to K fertilizer. Normally, the recommended procedures do not separate out the quantity of soluble or solution-phase K (K_{Soln} ; Fig. 1.1, pool 8) because the amount of K_{Soln} is generally minor when compared to the amounts of K_{Surf} (Doll and Lucas 1973; Knudsen et al. 1982). For example, an analysis of selected US soils found quantities of K_{Soln} varied between 1 and 30+ mg K kg⁻¹ soil under well-moistened conditions, while corresponding K_{Exch} levels ranged from approximately 20 to 850+ mg K kg⁻¹ soil (Brouder 2011). Regardless, K measured in a soil test of K_{Exch} (STK_{Exch}) is not the total K_{Exch} or an estimate of the quantitative sum of K_{Surf} and K_{Soln} but rather an index of the fraction or efficiency of this pool (E_{Exch}) that can be accessed by crop roots during a given growing season of crop cycle where

$$\text{STK}_{\text{Exch}} \cong K_{\text{Exch}} \times E_{\text{Exch}} \quad (1.7)$$

A large body of subsequent research generally supported Bray's assertion of K_{Exch} as the primary tool to assess K_{Soil} for many soils, but contradictory studies showing poor correlation between crop uptake and yield and various measures of K_{Exch} have also frequently occurred. For example, K studies of cotton grown on vermiculitic soils in CA, USA, found relatively poor relationships between yield and K_{Exch} (NH_4Cl -extractable K; Cassman et al. 1989). Related work demonstrated that K_{soil} could be better predicted from assays targeting the soil solution's relationship to the nonexchangeable soil K pools (K_{NonExch} ; Cassman et al. 1990; Brouder and Cassman 1994). Similarly, in a recent examination of soil K supply in US Midwest maize production, Navarrete-Ganchozo (2014) found K_{Exch} to be an insensitive predictor of soil K balance. This long-term K rate study demonstrated that, for some soils, the regionally accepted protocol for assessing K_{Exch} (NH_4OAc -Ext.; Brown 1998) failed to find differences in surface (0–20 cm) soil K dynamics, although cumulative crop K balances ranged from more than –400 to 400 kg K ha⁻¹

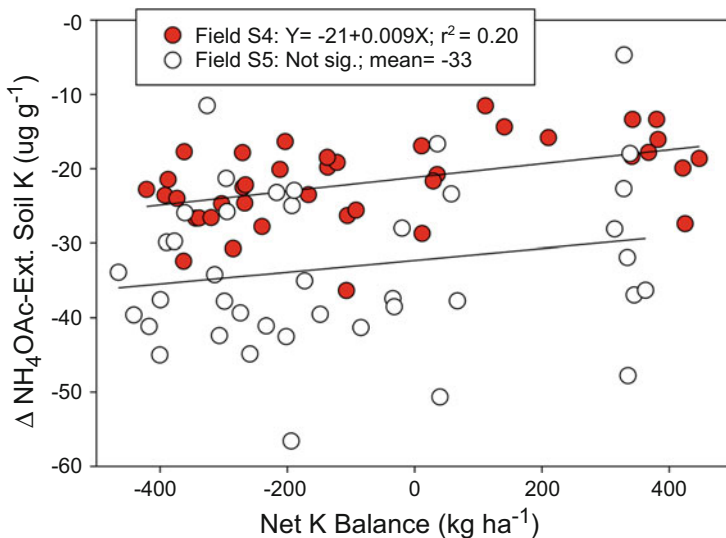


Fig. 1.6 Change in ammonium acetate extractable K ($\text{NH}_4\text{OAc-Ext. K}$) in surface soil (0–20 cm) between 1997 and 2010 plotted for two fields (S4 and S5) as a function of the net K balance (cumulative fertilizer K applied minus K removed in grain yields). Fertilizer K was added annually and biennially for cumulative applications ranging from 0 to 900 kg K ha^{-1} with all applications ending in 2002. (modified from Navarrete-Ganchozo 2014)

(Fig. 1.6). Such soils require expanding the characterization of K_{Soil} to be inclusive of any net contributions (flux from $>$ flux into) from interlayer K, structural K, and/or K in neoformed secondary minerals (Fig. 1.1, pools 10–13).

The theoretical function for the sum of soil pools “ j ,” where “ j ” represents pools 10 to 13 in Fig. 1.1, follows that for K_{Exch} (Eq. 1.7), where for each pool j , there is a quantity available (K_j) and an efficiency factor (E_j) to characterize the fraction of the use of pool “ j ” by the plant, crop or crop sequence in the growing season/cycle. The sum of the products of quantities and fractions for all for pools should represent the fraction of K_{NonExch} that is plant-available and accessed by plant roots:

$$K_{\text{NonExch}} = \sum_{j=\text{pool } 10}^{j=\text{pool } 13} K_j \times E_j \quad (1.8)$$

and

$$K_{\text{Soil}} = \text{STK}_{\text{Exch}} + K_{\text{NonExch}} \quad (1.9)$$

It should be noted that although K_{NonExch} has frequently been identified as an important contributor to K_{Soil} , the contributions of specific pools have been inferred from the soil test assays that have correlated well with plant or crop performance and from general knowledge of soil mineralogy. For example, chemical boiling in strong

acid (1 M HNO₃) has been used to measure K_{NonExch} (Knudsen et al. 1982; McLean and Watson 1985) and has frequently been inferred as releasing fixed K from interlayer locations, but it may also cause dissolution of K-bearing minerals (Barber and Matthews 1962; Martin and Sparks 1983). From a routine soil testing perspective, considering a framework that uses a two soil-pool model based on STK_{Exch} and an additional, routine or periodic test for potential contributions of K_{NonExch} to K_{Soln} (STK_{NonExch}) may be feasible where

$$K_{\text{Soil}} \cong f(STK_{\text{Exch}}, STK_{\text{NonExch}}) \quad (1.10)$$

where STK_{NonExch} is evaluated from a quick chemical assay of potential seasonal contributions of soil pools 9–13 (Fig. 1.1) to K_{Soln} and therefore seasonal crop uptake. Although selection of STK_{NonExch} based on mode of action could render this approach tailorable to soils with differing mineralogies, further partitioning of K_{NonExch} for attribution to a specific K pool may be of little practical value while adding significantly to analytical costs.

Alternatively, as proposed by Cassman et al. (1990), a two-pool model for K-supplying power could focus on the relationship between K_{Soln} concentrations and buffering power as assessed by a STK_{NonExch} single-point assay or fixation isotherm such that

$$K_{\text{Soil}} = f(STK_{\text{Soln}}, STK_{\text{NonExch}}) \quad (1.11)$$

where STK_{Soln} could be assessed by an assay of K concentration in saturated paste or diluted soil solution extractions (Rhoades 1982) such as 0.01 M CaCl₂ as proposed by Cassman et al. (1990). In theory, this last approach could approximate soil buffer capacity or the “quantity-intensity” relationship—the ability of the solid phase to replenish solution concentrations depleted by root uptake. In practice, single point measurements of STK_{Soln} and STK_{NonExch} provide only static insights into relative concentrations at the time of measurement and do not necessarily give insights into dynamic interactions among pools. At a minimum, the latter would require multiple assessments over time, and cost would scale accordingly. As Chap. 8 discusses, the mixed bed cation-anion exchange resin method provides a strong sink for K and can be used to estimate the rate of solution K replenishment in response to depletion by plant uptake. In most regions where soil testing has been developed for the purposes of making a K recommendation, STK_{Soln} and STK_{NonExch} tests have been used to explain the failure of STK_{Exch} to predict yield and fertilizer sufficiency but have not been subject to the extensive field correlation-calibration efforts necessary to develop them as the foundation for a recommendation. Regardless, current inconsistencies in the ability of potential routine measures of K_{Soln} and K_{NonExch} to improve recommendations with or without K_{Exch} as a covariate suggest that other covariate measures are needed for accurate prediction of K_{Soil} from soil testing information (e.g., Eqs. 1.10 and 1.11).

1.4.3 Exploring and Characterizing K_{Fert} and E_{Fert} : Important but Generally Overlooked?

In general, understanding E_{Fert} has been much less of a research concern for K as compared to N or P, not because K_{Fert} cannot be lost from or retained by soil, but because unrecovered K fertilizer has not been identified as an environmental pollutant. Most commonly available inorganic K fertilizers (soluble K salts of chloride, nitrate, or sulfate) dissolve rapidly in water, and insolubility, per se, is not considered an availability issue outside of multi-nutrient mixtures for fertigation. Thus, the K content of an inorganic fertilizer can be expected to appear in the soil solution (Fig. 1.1, pool 8) very rapidly after application, provided soil conditions are not too dry. Likewise, K introduced to soils in organic materials is also in the K^+ form and should appear rapidly in the soil solution as materials leach. The microbial mineralization-immobilization activity that confounds N recommendations is not a consideration. Thus, the major processes with potential to routinely reduce efficiency of fertilizer application are erosion and runoff (K_{Erode} , pool 4), leaching below the root zone (K_{Leach} , pool 5), and internal sink processes of fixation (K_{Fixed}) into interlayer sites (pools 10 and 11) or precipitation (K_{Precip}) as neoformed secondary minerals (pool 13). Thus:

$$E_{\text{Fert}} = (K_{\text{Fert}} - K_{\text{Leach}} - K_{\text{Erode}} - K_{\text{Fixed}} - K_{\text{Precip}}) / K_{\text{Fert}} \quad (1.12)$$

An early review of the literature suggested K_{Fert} leaching losses to be negligible on silt loam and heavier textured soils in US states of the Midwest and West (Munson and Nelson 1963). Even when such soils require subsurface agricultural tiles to improve drainage, losses of applied K appear low. Bolton et al. (1970) reported mean annual K concentrations of 0.95 and 1.23 mg L⁻¹ in drainflows of unfertilized and fertilized plots, respectively, with corresponding load losses of 0.6 and 1.1 kg K ha⁻¹ year⁻¹. More recent work found similar drainflow concentrations with no apparent impact of inorganic fertilizer rate (0 vs. 260 kg K ha⁻¹), source (manure vs. KCl), or cropping system (Fig. 1.7). However, applications to sandier soils are much more susceptible to leaching with the magnitude of loss expected to be proportionate to percolate volume with fluctuations reflecting timing, quantity and intensity of rainfall events, and quantities of K added (Bertsch and Thomas 1985; Chap. 3). Likewise, highly weathered tropical and subtropical soils are subject to higher leaching losses (Malavolta 1985), and quantities of K_{Fert} lost to leaching are likely widely variable. For such situations, soil fertility textbooks suggest that losses of 30% or more may occur without management to reduce loss, such as lower annual rates or split applications (e.g., Havlin et al. 2014), but peer-reviewed literature reports remain sparse.

Similarly, K_{Fert} lost to erosion and surface runoff can be impacted by the nature of precipitation events as well as by field slopes, fertilizer placement, and degree of incorporation. In 1985, Bertsch and Thomas (1985) characterized K losses to erosion of temperate soils as understudied and perhaps of greater magnitude than expected.

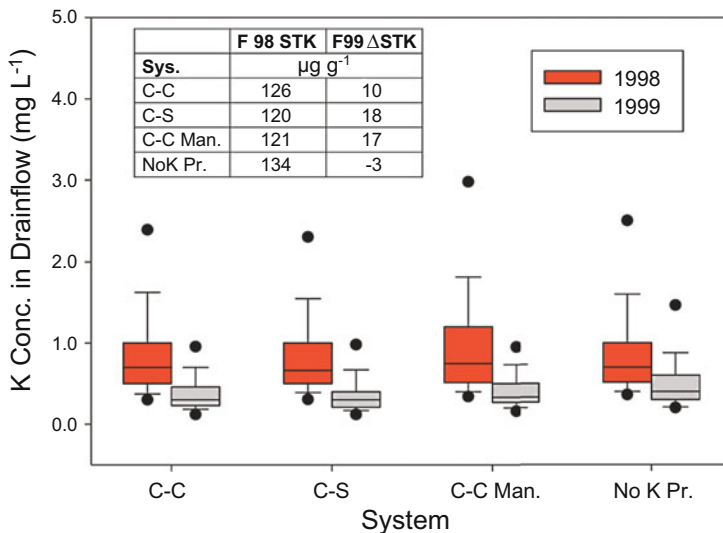


Fig. 1.7 Daily concentration in tile drainflows at the Purdue University Water Quality Field Station in 1998 and 1999 calendar years. Inorganically fertilized continuous corn (C-C; 20 treatment plots) and corn-soybean (C-S; 24 plots) rotations received 260 kg K ha⁻¹ as KCl in May 1999. Data for C-C plots receiving regular fall or spring applications of swine manure (C-C man; 8 plots) and an unfertilized restored prairie (no K Pr., 4 plots) are also shown. Sample number varies from 159 (no K Pr., 1998) to 987 (C-S, 1999) daily observations; box plots show 25th, median, and 75th percentile values, error bars indicate 10th and 90th percentiles, and solid circles are 5th and 95th percentiles. Inset table shows the mean soil test levels in the fall of 1998 and the change measured in the subsequent fall 1999 sample. (Brouder, unpublished data)

While not suggesting any specific proportion of K_{Fert} lost by this mechanism, these authors noted that conservation tillage should be helpful in reducing losses. In their chapter on K, Havlin et al. (2014) neither show K_{Erode} as a loss mechanism in their rendition of the K cycle nor discuss it in their text. In general, it appears little effort has been put into understanding K_{Erode} as a significant factor reducing the efficiency of K_{Fert} , although it may be an important consideration under an array of environmental and management conditions. For further discussion of K_{Leach} and K_{Erode} , see Chap. 3.

Unlike K_{Erode} , much attention has been paid in the literature to K_{Fixed} , especially in STK_{Exch} correlation-calibration studies when fertilizer rates well in excess of K_{Harv} do not appear to build STK_{Exch} as expected. For example, in the classic Cassman work discussed above (Cassman et al. 1989), cotton (*Gossypium hirsutum* L.) grown on soils with a history of intensive cropping without K fertilization was deficient in K but failed to respond to moderate rates of K_{Fert} . With repeated K additions, these authors observed an increase in apparent K_{Fert} uptake efficiency, which they attributed to partial saturation of K fixation by earlier fertilizer applications. Likewise, Navarrete-Ganchozo (2014) demonstrated that on K-fixing soils, the residual value of K_{Fert} was unobservable several years after halting aggressive

fertilizer additions even though large positive input balances remained (Fig. 1.6). As reviewed by Brouder (2011), when K is added to soils with 2:1 layer silicate clays (e.g., weathered micas, smectite, and vermiculite), nonhydrated K can fit into spaces between interlayer surfaces of clay mineral silicate sheets. In minerals with high charge density, K fixation between adjacent sheets can stabilize the overall structure and depress subsequent release of K_{Fixed} (Barber 1995). Factors decreasing the extent of K fixation include the presence of oxide precipitates on clay surfaces or in interlayer positions (e.g., Rich and Obenshain 1955; Horton 1959; Rich and Black 1964; Page and Ganje 1964), increased soil organic matter, especially mobile humic acid fractions (Cassman et al. 1992; Olk and Cassman 1995), and NH_4^+ addition (Bolt et al. 1963; Lumbanraja and Evangelou 1992; Brouder and Cassman 1994). In contrast, wet-dry cycling can drive net K movement into fixed positions, thereby reducing fertilizer efficiency (Olk et al. 1995; Zeng and Brown 2000).

Not surprisingly, in regions with long histories of soil test calibration work, suggestions to assess K_{Fixed} have focused on the same assays proposed for understanding of contributions of K_{NonExch} to K_{Soil} (discussion of Eqs. 1.10 and 1.11). For example, Murashkina et al. (2007) examined the standard $\text{NH}_4\text{OAc-Ext}$ assay for STK_{Exch} , a modification of the K isotherm method (Cassman et al. 1990), the 5-min sodium tetrphenylboron (TPB) assay, and soil texture with the goal of developing a quick test for routine determination of K_{Fixed} . Because it involves a precipitation reaction that removes K from the soil solution as a sink (like a root would be), the TPB extraction has been advanced as a more mechanistic protocol when compared to strong acid extractions (1 M HNO_3) (Cox et al. 1999). Similarly, Murashkina et al. (2007) found the modified Cassman method was a rapid and reliable method for predicting fixation potential, while TPB was identified as useful with a measure of STK_{Exch} to predict K already fixed or a reduction in fixation potential. It is important to note that isotherm assays cannot distinguish between the mechanisms of K loss from the soil solution to K_{Fixed} and K_{Precip} much as TPB or strong HNO_3 extraction cannot distinguish among pools contributing to K_{NonExch} . Regardless, despite research identifying protocols to assess K_{Fixed} and/or K_{Precip} , recommendation frameworks have yet to be modified to include an explicit consideration of these measures in an estimate of E_{Fert} .

Finally, K returned in unharvested residues (K_{UnHarv}) is significant and should reduce K_{Fert} when compared to a system where residues are removed. But the efficiency of this return is understudied, and the K_{UnHarv} fraction has been largely ignored as an explicit factor in recommendation frameworks. It is interesting to note that Stanford (1973) did not explicitly consider N returned in residues even though N management research focused on residue N contributions to subsequent crops was already being actively pursued. For example, Shrader et al. (1966) had demonstrated that maize (*Zea mays* L.) following oats (*Avena sativa* L.), meadow, and soybean acquired $>80 \text{ kg N ha}^{-1}$ in fertilizer equivalent from the residues when compared to maize grown without rotation. In their comprehensive expansion of Stanford's equation, Morris et al. (2018) explicitly include a fertilizer equivalent factor for the soil N supply attributable to the legume and an efficiency factor for the fraction that may be taken up by the plant.

In living plants, K is not metabolized and forms only weak complexes in which it is readily exchangeable (Wyn Jones et al. 1979). Thus, K_{UnHarv} left on or in the soils in residues will be returned to the soil solution as the tissues decompose. K_{UnHarv} can represent a significant input for the next crop in a rotation. For example, modern maize and soybean varieties can return quantities of K ranging more than 40–200 and 80–150 kg K ha⁻¹, respectively, depending on growing conditions and degree of luxury consumption (Fernández et al. 2009; Wu et al. 2014; Gaspar et al. 2017; Zhang et al. 2012). As discussed above (Sect. 1.4.1), K HI in grain crops can be expected to be highly variable. Wu et al. (2014) report K HI values ranging more than 0.1 to 0.45 for maize grown under optimum and super-optimum soil K (CV = >25%). Thus, the limitations of using grain dry matter yields to estimate K_{Plant} (Eq. 1.5; Sect. 1.4.1) extend to estimating K_{UnHarv} . Further, research to date is insufficient to determine whether E_{Fert} for inorganic fertilizers and manures could also apply to residues. In temperate systems with conservation or no-tillage, sparse data suggest as much as 80 and 90% of K in maize and soybean residues at the soil surface, respectively, may be leached from the residue by planting time in the following spring (Oltmans and Mallarino 2015); presumably the remaining residue K will be leached from the residue within the growing season. Once residue K enters the soil solution, factors that reduce the efficiency of added K (K_{Leach} , K_{Erode} , K_{Fixed} , and K_{Precip}) can be expected to be similar to those affecting K_{Fert} . However, how residue is handled will likely impact losses in surface runoff. Simulated rainfall studies suggest K concentrations in runoff could initially be substantially higher from no-till soybean fields compared to conventionally tilled soybean fields (Bertol et al. 2007), but typical erosion-related losses of K_{UnHarv} for common residues and their managements are largely unknown.

In sum, with the caveat that almost all the K_{UnHarv} enters the soil solution, the basic Stanford equation (Eq. 1.2) can be expanded for K to

$$E_{\text{KAdded}} \times (K_{\text{Fert}} + K_{\text{UnHarv}}) = K_{\text{Plant}} - K_{\text{Soil}} \quad (1.13)$$

where a generic efficiency factor (E_{KAdded}) applies to both K_{Fert} and K_{UnHarv} . Then K_{Fert} is estimated as

$$K_{\text{Fert}} = [(K_{\text{Plant}} - K_{\text{Soil}}) \div E_{\text{KAdded}}] - K_{\text{UnHarv}} \quad (1.14)$$

As indicated by the discussion above, E_{KAdded} is challenging to measure directly and has been approximated as apparent crop recovery efficiency (RE_K ; Cassman et al. 2002). At a minimum, determination of this factor requires omission plots to compare K_{Soil} to total plant uptake ($K_{\text{Soil} + X}$) at a specific fertilizer rate “X” (K_{FertX}), using Eq. (1.2) rearranged as

$$E_{\text{KAdded}} \cong \text{RE}_K = (K_{\text{Soil} + X} - K_{\text{Soil}}) / K_{\text{FertX}} \quad (1.15)$$

This approach aggregates the disparate impacts of crop-specific K_{UnHarv} , soil mineralogy, and agroecozone environmental parameters that can influence E_{KAdded}

(Chaps. 4 and 5). With enough data, this differential approach could permit identification of categorical classes for $E_{K_{\text{Added}}}$ for routine use in recommendation frameworks. To date, however, existing data resources are too fragmented and incomplete for a robust implementation of this approach. Many K rate studies have not assessed K_{Plant} (as discussed in Sect. 1.4.1). Still, analysis of existing data might be sufficient to determine if this approach to understanding efficiency could be useful in an expanded mass balance recommendation framework.

1.4.4 Potassium Recommendations Without Soil Tests

Although soil tests are widely employed as the basis for K recommendations, there are many places and circumstances where they are not used. Soil testing services are not ubiquitous, and many areas do not have the needed facilities, logistics, or quality control mechanisms in place. Additionally, even when soil testing is available, a particular farmer may have no recent soil test information in hand at the time when a recommendation needs to be made. There are also situations where soil tests, even if available, do not provide reliable diagnostic information. We discuss two K recommendation approaches that can be used either with or without soil test information.

1.4.4.1 Recommendations Based on Nutrient Removal

When plant biomass is removed from a field, the K contained in that biomass is also removed. To maintain K levels in soils, K needs to be added to replace the K removed (K_{Harv}). A **maintenance fertilizer rate** is *the amount of K that replaces K removed by crop harvest*. This rate can be expressed as $K_{\text{Fert}} = K_{\text{Harv}}$. Ideally, removal is measured by analyzing samples of the harvested biomass for dry matter content and nutrient concentration. Most common, however, is to estimate the quantities of K removed, using average values of K concentrations (K_{AveConc}) published in recommendation guidance documents, such as Vitosh et al. (1995) and Mallarino et al. (2013). In production settings, these averages are typically treated as constants. The maintenance rate is estimated akin to Eq. (1.5) as

$$K_{\text{Fert}} = K_{\text{Harv}} = (\text{Yield}) \times K_{\text{AveConc}} \quad (1.16)$$

As discussed in Chap. 3, treating K_{AveConc} as a constant does not acknowledge any variability, leading to maintenance rates that may not accurately replace the K that was removed by harvest.

Maintenance rates are necessary for sustaining soil K levels; however, as Olson et al. (1987) observed, they do not consider the economically optimum rate of K for a given cropping season. To examine the implications, we look at two scenarios at opposite ends of the spectrum.

First, we consider the case when levels of plant-available K in soil are already adequate or nearly adequate for expected levels of crop production. In this case, the cost of K applied at maintenance rates will not be profitable for that season, since the yield and revenue increases needed to recover the costs will not be realized. Farmers who own the land that is fertilized may have sufficient capital and long-term soil management objectives to absorb this cost in the short term to realize the longer-term gains of sustained soil fertility and crop productivity. However, if the farmer who is paying for the fertilizer is renting the land, and the rental agreement does not have provisions for the farmer to recover this cost, then the landowner, not the farmer, will be the one to gain from the maintenance application.

Second, we consider the case when levels of plant-available K are very low. In this case, a maintenance rate may be too low to realize the fully attainable crop responses and revenue increases. In recommendation approaches using algorithms to optimize net returns in one cropping season, recommended K rates can be above maintenance rates (calculated from Kaiser et al. 2018). Using maintenance rates in this scenario leads to two missed opportunities: (1) realizing the full yield and revenue increases possible and (2) increasing soil fertility for the subsequent season or seasons. When application rates exceed maintenance rates, the K supply in the soil increases, assuming that there are no losses to pools 3–5 or 10 in Fig. 1.1.

Maintenance rates have been combined with soil test information in some recommendation systems (Vitosh et al. 1995). In those algorithms, they are recommended when levels of soil fertility have reached levels that are considered optimum for crop production.

1.4.4.2 Recommendations Based on Plant Nutrient Uptake and Yield

Perhaps the most well-developed approach that can be used with or without soil test information is the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model (Janssen et al. 1990). It was designed as a land productivity evaluation tool, with predicted maize yield as the primary model output. Yield was predicted from both quantities of potentially available soil nutrients and plant nutrient uptake (originally developed for N, P, and K). QUEFTS was developed from data from Kenya but has since been widely used as a framework for K recommendations in other countries and for a variety of crops, including banana (*Musa* spp.; Nyombi et al. 2010), cassava (*Manihot esculenta* Crantz; Byju et al. 2012), maize (*Zea mays* L.; Janssen et al. 1990), oilseed rape (*Brassica napus* L.; Cong et al. 2016), peanut (*Arachis hypogaea* L.; Xie et al. 2020), potato (Kumar et al. 2018), radish (*Raphanus raphanistrum* subsp. *sativus* (L.) Domin; Zhang et al. 2019), rice (*Oryza sativa* L.; Witt et al. 1999), soybean (Jiang et al. 2019), sweet potato (*Ipomoea batatas* (L.) Lam.; Kumar et al. 2016), taro (*Colocasia esculenta* (L.) Schott; Raju and Byju 2019), and wheat (*Triticum aestivum* L.; Chuan et al. 2013). These crops rely on new uptake of nutrients from the soil during the season to meet most, if not all, of their total uptake requirements. To our knowledge, tree crops have not been evaluated with QUEFTS, likely because of the logistical challenges of

measuring uptake. We could also find no examples where perennial forages were evaluated with QUEFTS.

QUEFTS models how the potentially available soil supplies of three nutrients interact to affect total uptake and yield. Using N, P, and K as an example, the uptake of K is predicted from potential soil supplies of K and N; then it is predicted a second time from potential soil supplies of K and P. The lower of the two K uptake estimates is used, since it is considered to be more efficient (Witt et al. 1999) and limits the bias introduced by luxury consumption. From this lower uptake, two yield estimates are made, based on lower and upper boundary lines encompassing observations (usually numbering in the hundreds) of K uptake and yield. The slope of each boundary line is yield divided by total nutrient uptake. This slope is termed “internal efficiency.” The upper boundary line represents yields associated with maximum K dilution, and the lower boundary line represents yields associated with maximum K accumulation. The creation of paired boundary lines is repeated for the other two nutrients. A systematic comparison of all yield estimates, considering two nutrients at a time, results in a final, average yield estimate.

Liebig’s law of the minimum is a fundamental concept in the way QUEFTS evaluates nutrient interactions. Yields are limited by the most limiting of the three nutrients. For a given yield, if total K uptake is lowest (maximum dilution), and uptake of N and P are higher, then K is considered yield-limiting. If total K uptake is highest (maximum accumulation), then one or both of the other nutrients may be limiting, or luxury consumption may be occurring. The model makes it possible to determine optimum uptake levels of nutrients that keep any one nutrient from being limiting (Witt et al. 1999).

When QUEFTS was developed, it relied on soil tests as measures of potentially available soil nutrients. Interestingly, the predictor of potentially available K supply was not exchangeable K alone, but exchangeable K combined with pH, organic carbon, and cation exchange capacity (Janssen et al. 1990). In a later application of the QUEFTS model to irrigated rice systems, Dobermann et al. (1996) developed the concept of effective soil K-supplying capacity. They defined it as “. . .the amount of K a crop takes up from indigenous resources under optimum conditions—i.e., when all other nutrients are amply supplied and only K is limiting. . . .” Operationally, they measured it from total K uptake in rice grown where N and P had been applied, but not K. Analogous calculations were done for N and P. The emphasis was on the quantities of nutrients the plant actually took up from the soil, rather than what the soil could potentially provide. The collection of large quantities of nutrient uptake data enabled the application of QUEFTS to situations where soil tests were not available.

The primary measurements that are needed by QUEFTS are yield, uptake, and rates of fertilizer applied. In experimental trials, to calculate the effective soil nutrient capacities of each nutrient, three treatments are required: one that omits N (PK plot), another that omits P (NK plot), and a third that omits K (NP plot). To calculate the recovery efficiency of a given nutrient (Eq. 1.15), the total uptake in the omitted plot (NP, for instance, or K_{Soil} in Eq. 1.15) is subtracted from that of the plot where all three nutrients were applied (NPK or $K_{\text{Soil} + \text{X}}$ in Eq. 1.15) and then divided by the

rate of the given nutrient (K in this example or K_{FertX}) applied in the NPK treatment. This data requirement of QUEFTS led to a basic four-treatment “omission plot” design (PK, NK, NP, NPK) that has been deployed widely, both on research stations and farmers’ fields. Large databases have been developed from these trials (like the IRRI Mega Project referenced in Witt et al. (1999)), providing proxy data that can be used when local data do not exist.

Although QUEFTS was developed as a land evaluation tool, its framework has been expanded upon to develop recommended rates of N, P, and K. To do this, Guiking et al. (1995) considered the change in uptake and yield that resulted from applying fertilizer. Unfertilized yield was predicted from the effective soil K-supplying capacity—the uptake where no K was applied. Guiking et al. (1995) then considered what happened under fertilization. Fertilization was added to the soil K supply; however, only a fraction of the fertilizer rate (E_{Fert} or recovery efficiency) was taken up by the plant. By multiplying the fertilizer rate by E_{Fert} , the change in plant uptake was estimated. This higher uptake was then used by QUEFTS to estimate fertilized yield. Based on the yield increase and the quantity of fertilizer applied to generate that increase, economic returns could be calculated and economically optimum rates determined through iteration.

More recently, Pampolino et al. (2012) developed Nutrient Expert[®], a software tool that builds upon QUEFTS to generate nutrient recommendations for cereal farmers. Nutrient Expert is built on a large database of data from omission trials. In these trials, data collected include yield, nutrient uptake, soil test information (where it exists), crop sequence, crop residue management practices, soil fertility status, and water management information. Information on farmers’ existing yields are used as background for conducting omission plot trials. Nutrient Expert[®] integrates all of these factors to create nutrient recommendations that consider attainable yield levels, expected crop responses, nutrient input and output balance, production risks, and economic returns.

1.5 Diagnostics Development: The Undelivered Promise of “Big Data”

Before discussing pathways to improve the use of the K cycle in recommendations, it is informative to move beyond the existing tools (e.g., a calibrated K exchange test) to reflect on the process of diagnostic development and the extent to which any single measurement can embody all the knowledge necessary to make a decision. The use of soil testing as an essential tool in managing fertilizer has its foundations in the seminal work conducted in the 1920s and 1930s (Melsted and Peck 1973). In the case of soil testing-based approaches to K fertilizer recommendations, the majority of research focused on developing chemical extraction procedures for assessing quantities of plant-available K in crop rooting zones. As remarked by Colwell (1967), “A measurement qualifies to be termed a soil test for a particular nutrient

if, and only if, it provides information on the fertilizer requirement of a crop for that nutrient.” Generally, the term correlation has been used to characterize the process of relating nutrient uptake and/or yields to the quantity of a nutrient extracted by a particular soil test, while calibration refers to the experimentation needed to characterize the meaning of the soil test result for a crop response (Dahnke and Olson 1990). Much of the initial research on calibration of soil K tests focused on delineating responsive from non-responsive soils and categories for major differences in degrees of crop response (Bray 1944; Cate and Nelson 1971; Olson et al. 1958; Rouse 1967). Research in the latter decades of the twentieth century has tended to focus on the actual quantities of fertilizer needed to obtain maximum or profitable yields and experiments relating yields to fertilizer increments (Dahnke and Olson 1990; Welch and Wiese 1973). Regardless, any individual measurement must be underpinned by sufficient correlation and calibration research if it is to meet Colwell’s criterion of providing generalizable information across space and time on a crop’s fertilizer requirement. Certainly it would be surprising to identify a result that is universally useful and applicable.

1.5.1 Data Limitations: Historic and Current

The development of a robust diagnostic is inherently a “big data” enterprise; indeed most K measurement(s), whether soil or tissue assays, were never intended to embody all knowledge necessary to guide management. Common approaches and best practices for soil test correlation and calibration are well documented in the literature (Cope and Rouse 1973; Hanway 1973; Melsted and Peck 1973; Dahnke and Olson 1990), but recurring themes dating from the earliest of these reports are (1) the need for large numbers of field studies and sufficient data to quantify the effects of important controlled (e.g., crop or tillage) and uncontrolled (e.g., weather) system variables and their interactions and (2) the inadequacy of resources to acquire those data. In their overview of soil testing principles Melsted and Peck (1973) remarked on the tenuous nature of the relationship between yield and the corresponding level of an available nutrient in the soil. In 1967, Tisdale stated that research concerning soil test development was under-supported because science administrators viewed as low priority the “unravelling of a highly complex functional relationship existing among plant growth, plant nutrient supply, and numerous environmental factors.” Hanway (1973) echoed this sentiment, implying that the making of agronomy into a quantitative science was impeded by the inability to conduct “adequate field experiments to provide the data required. Such experimentation is not easy, and it is not cheap, but there is no adequate alternative.”

The hazards of small studies with sparse data include low statistical power, model overfitting, lack of reproducibility, and a reduced likelihood that a statistically significant result represents a true effect that is generalizable (Brouder et al. 2019). For example, a 2-year, single location correlation study produced a statistically significant relationship between maize yield and soil test K (STK) that implied a

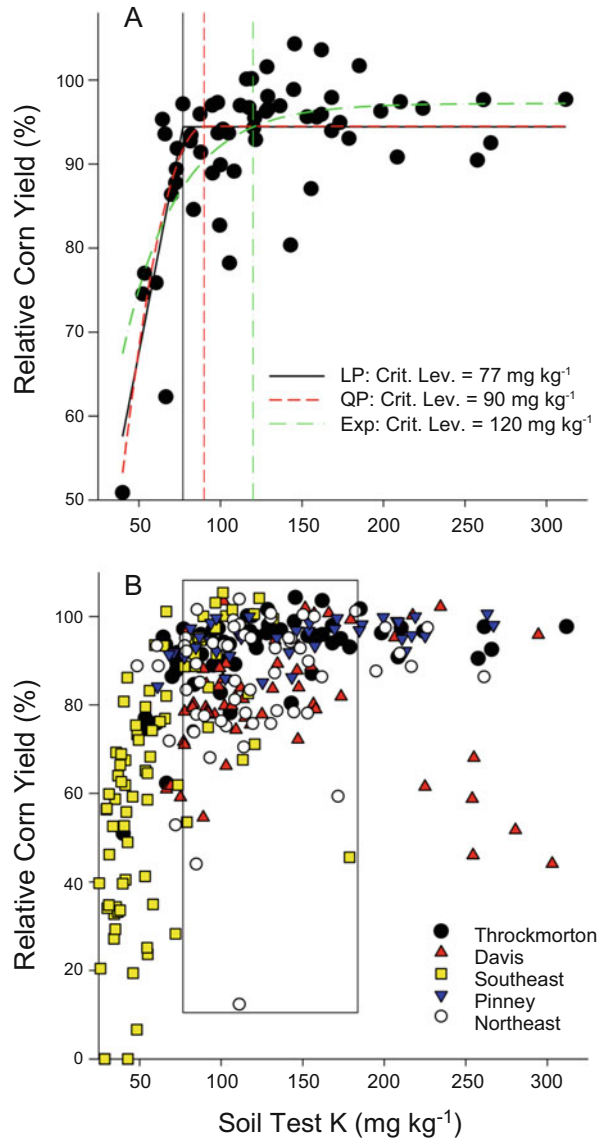
critical level that was definitive (Fig. 1.8a). Further, access to desktop computing permitted easy exploration of multiple empirical models with selection of the model and associated critical level based on best professional judgment regarding farmer perceptions of risk. Analysis of the correlation data demonstrated that common statistical models may perform similarly in explaining the variation among observations but identify critical levels that vary almost twofold (77 vs. 120+ mg kg⁻¹). Regardless, analysis across all five locations in the study demonstrated that the modeled correlations were not generalizable across multiple locations because substantial variation in relative yield was present at STK values ranging from 80 to 180 mg kg⁻¹ (Fig. 1.8b).

For STK correlation and calibration, the lack of generalizability of significant small studies to other locations and across multiple years is common (e.g., Navarrete-Ganchozo 2014). Historically, insufficient data and overly localized correlation/calibration research combined with a lack of coordination among researchers contributed to the development of conflicting recommendations for the same or similar crop-soil systems (Tisdale 1967). In the USA, arbitrary, geopolitical differences in recommendations based solely on STK persist, reflecting a dearth of resources to collect and rigorously analyze data including important covariate and metadata. Additionally, lack of funding has largely restricted the evaluation of new soil assays to laboratory comparisons with existing protocols. New tests are being implemented with no or minimal field evaluation, a practice expected to introduce more unexplained variation among results (Gartley et al. 2002). Thus, the use of hypothetically important categorical (e.g., soil series, subsurface soil K supplies; Kelling et al. 1998) and/or continuous (e.g., cation exchange capacity; Vitosh et al. 1995) covariates in recommendations currently lack scientific support despite the now almost universal availability of advanced computing to facilitate covariate exploration.

1.6 Opportunities Moving Forward

The minimal extent to which a mass balance approach has been successfully used in existing K recommendations—despite being the theoretical underpinning—became widely apparent with the advent of precision technologies. In early implementation of variable rate technologies, there was both a focus on K and an implicit expectation that collecting spatially dense soil samples and applying existing recommendations to soil test results would generate a soil- and crop-specific rate recommendation (Mulla and Schepers 1997; Wollenhaupt et al. 1997) that would be more profitable than a whole-field, uniform application. Subsequent research has been sufficient to demonstrate the fallacy in assuming the existing, generic, tabular recommendations can be disaggregated in a meaningful way. We have learned that key assumptions, such as linkages between K and CEC and standard values for anticipated STK changes with fertilization and crop removal, are either not universal or are generally incorrect (e.g., Navarrete-Ganchozo 2014; Fulford and Culman 2018; Chap. 10).

Fig. 1.8 Relationship between relative maize (*Zea mays* L.) yield and soil test K in surface soils (0–20 cm; $\text{NH}_4\text{OAc-Ext}$) in 2005 and 2005 at (a) one location (Throckmorton) and (b) five locations in Indiana, USA. (adapted from Navarrete-Ganchozo 2014)



1.6.1 Mechanistic Modeling

Mechanistic simulation models are intended to represent all system processes and attributes relevant to crop growth and development, including nutrient cycling and losses. To date, mechanistic models have been viewed primarily as research tools for hypothesis testing and predicting outcomes for the complex, system-level interactions that may occur when individual or suites of system parameters vary over their

known biogeochemical and physiological ranges. As such, the rigorously verified mechanistic model has the potential to (1) identify system parameters that drive outcomes (e.g., via sensitivity analysis), (2) serve as a foundation for a simplification that provides for limited input of the critical on-farm data necessary to a site- or soil-specific recommendation, and (3) identify knowledge gaps via model failure (Brouder 1999). Models could serve these purposes in developing improved K management strategies, provided the K cycling processes have been fully and explicitly tested.

Modeling nutrient uptake has evolved from the seminal work of Nye and Spiers (1964) who developed mathematical expressions describing mass flow and diffusion of nutrients to a root segment, to an array of computational tools that help explain and predict K behavior in agroecosystems (Table 1.2). These models vary in focus, ranging from mechanistic models to more general integrative models with inference space at the ecosystem level. These models also differ in their spatial (nanometer to watershed) and temporal (sub-second to year) scales. Some models were purpose-built, with the primary goal of understanding nutrient uptake, including K, from the onset. This includes POTAS (Barnes et al. 1976; Zhang et al. 2007) and the Barber-Cushman model (Classen and Barber 1976). Other K models were adapted from computational tools originally developed to study other ecosystem processes. For example, PROFILE (Holmqvist et al. 2003) was initially developed to calculate critical loads for acid deposition in forest soils but later was modified to predict K release as soil minerals weather. Similarly, SWAT-K, used to estimate environmental K losses at the watershed scale (Wang et al. 2017), was developed by altering the Soil Water Assessment Tool (SWAT) hydrology model. Many models have undergone continuous improvement while retaining the same name (e.g., DSSAT). Improvements in others have resulted in model rebranding (Barber-Cushman to NST 3.0; COMP8 to SSAND to PCATS) (Lin and Kelly 2010). Many of the most successful models were created by teams including expertise from both the physical and agricultural/biological science domains (e.g., Barber-Cushman; DSSAT). At least some of the early models are no longer practically available for use by practitioners (e.g., Barber-Cushman and NST 3.0).

Critical to successful model development is access to data needed for calibration and validation. Barnes et al. (1976) highlighted the need for additional data from more cultivars, crop species, sites and soils to improve the accuracy and precision of their K and N model. Decades later, constraints imposed by limited availability of quality data unfortunately persist (Janssen et al. 1990; Boote et al. 1996). Rosenzweig et al. (2013) indicated that experimental data for most agricultural models tends to suffer from several common problems including: aggregation across sites and/or experiments, making it difficult to assign variation in agronomic performance to local climate and soil properties; absence of site-specific management information (e.g., metadata like planting date, pest control, tillage, soil characterization, or cultivars); and inexplicable yield results that cannot be readily attributed to environment or management. Additional K datasets are still needed to validate models, improving their accuracy and precision and extending their inference space (Lin and Kelly 2010; Wang et al. 2017). Specific examples of knowledge

Table 1.2 Summary of some models that could be or are used to understand potassium dynamics in agroecosystems

Model type	Fundamental/mechanistic: soil and plant component	Process-based: soil and plant process	Whole plant and whole soil: Crop growth models	Ecosystem scale: Seasonal timeframe	Ecosystem scale: Multi-year timeframe
Example models:	HYDRUS 1-D; PROFILE	Barber-Cushman; HYDRUS 2-D; FUSSIM2; continuum/multiscale; NST 3.0; SSAND; PCATS	APSIM; QUEFTS; DSSAT; EPIC; POTAS	APSIM; DSSAT; EPIC	AGNPS; SWAT-K; OVERSEER
Spatial scales:	nm– μ m	mm–cm	dm–m	m–ha–field	Field—watershed
Temporal scales:	μ s–min	min–hours	days–months	1–12 months	>12 months
Examples of processes:	Cation exchange processes; adsorption-desorption of ions; cell membrane transport of nutrients	Water and nutrient uptake by roots; root growth and morphology; nutrient concentration impacts on nutrient uptake; genotype and phenotypic expression	Crop growth, nutrient uptake and yield; cultivar effects on nutrient uptake	Seasonal weather patterns; single crop systems, double cropping systems; spatial and temporal variability of soil properties	Multi-year weather and climate; multi-year rotations; spatial and temporal variability of soil properties
Examples of parameters:	Soil properties: pH, organic matter, particle size distribution, aggregation, clay mineral distributions; genetic and physiological control on nutrient use efficiency		Field-scale phenotypic and genotypic variation; soil test correlations; genotype \times environment \times management; linkage to econometric crop production models		
References:	Holmqvist et al. (2003), da Silva Santos et al. (2015)	Classen and Barber (1976), Satpute and Singh (2017), Heinen (2001), Mai et al. (2019), Lin and Kelly (2010)	Scanlan et al. (2015a, b), de Barros et al. (2004), Smaling and Janssen (1993), Janssen et al. (1990), Jones et al. (2003), Zhang et al. (2007), Barnes et al. (1976), Wang et al. (2017), Wheeler et al. (2003), Young et al. (1989)		

Models are grouped by type and vary in relevant temporal and spatial scales. Typical model outputs and inference spaces also are indicated

and data needed to improve K model calibration and/or validation include regulation of K luxury consumption, K adsorption/desorption and weathering of soil minerals, root morphology and mass impact on K uptake, soil moisture effects, transpiration rate impact on K uptake, and partitioning of K between shoots and roots, among others (Greenwood and Karpinets 1997; Holmqvist et al. 2003; Zhang et al. 2007; Scanlan et al. 2015a, b). It is hoped that ongoing national and international initiatives in open science and open access of publications and data will improve data availability for future modeling efforts.

1.6.2 Knowledge Gaps

Moving forward requires a careful assessment of the knowledge gaps and prioritization of investments with the highest probabilities of significantly advancing the science supporting K management. As discussed above (Sect. 1.2), a robust K recommendation must be complex enough in its components to represent important differences in biophysical and socioeconomic contexts but simple and cost-effective enough to be useful and efficiently used by the practitioner. Hence, explicit consideration must be given to whether or not K cycle parameters deemed scientifically important for an evidence-based K recommendation are practically assessable and whether cost-effective measurements of proxy variables have been fully explored. For example, the use of in-field elevation maps or telethermometry may prove more practical than soil sensors for determining localized moisture stress influencing K flux. Likewise, priorities of scientists must be balanced by those of practitioners. Important research foci include:

- *Correlation and calibration studies that explicitly test for covariates and important biophysical influencers of the K cycle:* What is clearly not needed are more primarily two-factor correlation calibration studies that focus on a putative, universal diagnostic (e.g., STK) and yield. As demonstrated above (Fig. 1.8b), covariate and metadata must be sufficient to explain variation in yield response across locations and yields to create a relationship to yield that is generalizable across space and time. While more expensive, long-term, multivariate studies not only improve the understanding of the crop-soil K cycle but would facilitate inclusion of important secondary biophysical influencers into a K recommendation (Fig. 1.2).
- *A better understanding of soil assays by mode of action:* Chap. 8 highlights the theoretical design features of different soil tests and proposes the choice of a test be based upon the expected duration of the meaning of a test result to crops and cropping systems of differing duration (short annual versus multi-harvest perennial). Such an approach is currently not used in most recommendation systems. In the USA, for example, recommended soil tests for routine testing are almost all assays of K_{Exch} with variations in extractant chemistry associated with geopolitical borders and not cropping system attributes (Nathan and Gelderman 2015).

- *Alternative approaches that are not grounded in soil testing and require development of large soil databases and routine, on-farm soil testing:* For regions and crops that have not historically relied on soil testing, developing soil tests and testing programs may be cost-prohibitive. Additionally, for some major production systems, K_{Soil} shows little relationship to quick chemical assays. For example, Dobermann et al. (2003) used omission plots in irrigated rice to characterize K_{Soil} and hypothesized that the approach held more promise for efficient development of site-specific recommendations.
- *Mechanistic and novel, empirical modeling of the K cycle:* The research needs for improved mechanistic modeling of the K cycle are highlighted above (Sect. 1.6.1). Additionally, machine learning and artificial intelligence approaches hold great promise for synthesizing K cycle data. Methods such as machine learning are tolerant to complex data characteristics (e.g., nonlinearity and outliers) (Brouder et al. 2019) and could be used to both detect patterns to underpin decision trees and to identify important proxy variables that are easy to assess. They can also automatically incorporate new information, creating opportunities for recommendations that are self-improving, potentially with on-farm data. Artificial neural networks are receiving increased interest as tools to explore input-output relationships in complex, agricultural systems where understanding remains incomplete (Yang et al. 2018; Liakos et al. 2018; Welikhe 2020).
- *K synthesis science:* Systematic review (SR), with or without application of meta-analysis statistics, is a well-recognized framework for translating knowledge into evidence-based policy and management practice. Cumulative systematic reviews permit efficient reanalysis of a relationship, effect, or efficacy of a practice as new data accrues. SR has long been considered a discrete field of research in medicine (Sackett and Rosenberg 1995; Cucherat et al. 1997; Jadad et al. 1998) and the gold standard for synthesizing research into a clinical practice and decision-making (Mulrow et al. 1997). Reports in the agricultural literature have highlighted the potential for routine use of systematic reviews to improve the quality of the primary literature and its use in evidenced-based decision-making (Philibert et al. 2012; Eagle et al. 2017; Brouder et al. 2019). The concept of developing minimum dataset guidelines to ensure small research studies can be synthesized (Brouder and Gomez-Macpherson 2014) has emerged as an important component of multi-investigator research networks and collaboratives. Proof-of-concept research is also needed regarding the value of integrating on-farm data with research data in developing site- and soil-specific K recommendations.
- *Probability, risk, and economics:* Although K recommendation frameworks have frequently associated an STK interpretation category (e.g., low, medium, high, very high) with the probability of response to fertilizer (50–0%) (Havlin et al. 2014), the probability of the response being of a particular magnitude was not included, as data typically were insufficient. Indeed, response probabilities for STK categories do not appear to have been rigorously evaluated despite their importance to farmer decision-making. The socioeconomic aspects of K management are beyond the scope of this chapter and book, but evaluation of any

improved framework should include a partial budgeting analysis to evaluate the changes in revenues and costs associated with applying the new recommendation compared to prior farmer practice.

1.6.3 Tools and Strategies, Data, and e-Infrastructure

Given the costs of conducting the system-level K cycle research required for strengthening our understanding, coordination among researchers, rigorous synthesis of new with existing studies, and application of a broad array of cyber-tools will all be paramount. Likewise, the planning for and sharing of structured data must become the norm, as most promising analytical strategies are data intensive. Scientists have reached near universal agreement that data sharing has value and advances research toward solutions to complex problems (e.g., Kim and Stanton 2016). In their analysis of the opportunities afforded to agriculture by data sharing, Brouder et al. (2019) argue that data sharing and the e-infrastructure needed to facilitate it will enhance the reliability of results and increase public trust in and use of agricultural science. Important data resources not currently available for synthesis and key attributes of a system to facilitate sharing and science synthesis to improve K recommendations are described here in brief.

1.6.3.1 Underutilized Data Sources with Potential

At present, the peer-reviewed literature is the primary source of data that is synthesized in systematic reviews and used to develop and verify the components of mechanistic models. Yet, for a variety of reasons, better characterization of study weights and effect sizes in statistical meta-analyses can be achieved with the use of the original study data than with extracted treatment means and their reported variance statistics (Cooper and Patall 2000). Likewise, mechanistic models can be more rigorously assessed with original data. Peer-reviewed journals tend to emphasize novel results (Fanelli 2012), thereby distorting the foundations of evidence-based practice by excluding confirmatory, null, or negative results. While numerous factors can contribute to irreproducible or non-generalizable results, solutions for improving the quality of science consistently stress complete reporting inclusive of data access (Begley and Ioannidis 2015; Button et al. 2013; Goodman et al. 2016). Furthermore, anecdotal evidence suggests that much of the data collected in previous and ongoing STK correlation and calibration research is inaccessible today—even in synthesized form—as publication in the less rigorous grey literature (e.g., newsletters, local- or state-level reports, conference proceedings) was and remains common when the goal is to test or adapt a peer-reviewed result for local constraints or conditions and farmer preferences. Such grey literature can be difficult to even identify (Debachere 1995). Mechanisms to ensure visibility and validity for the grey literature and data not associated with peer-reviewed publications along with

recovery of legacy data associated with journal publications could greatly increase quality data available for synthesis.

Beyond research, other data that have the potential for improving site and soil specificity of a K recommendation include private research and on-farm data. Nutrient management research in the private sector typically remains in-house, although entities from that sector may be willing to share a portion of their research data to find new approaches with promising business opportunities or to bring additional credibility to their products through independent scientific evaluation. Additionally, combining on-farm data with research data could extend the inference space of research results. Few expect funding allocations to agricultural research to increase dramatically in the coming years (see USDA ERS 2018 and EPAR 2017 for trends in public and private support) making it even more imperative to improve efficiency of data collection and the use and reuse of existing data. However, the quantity of on-farm data generated by crop producers is projected to increase exponentially (BI Intelligence 2015). Harnessing these data for research on management recommendations is widely considered an untapped opportunity to leverage public research investments. Still, privacy, security, ownership, and intellectual property concerns need to be addressed when accessing and using privately generated data from any source.

1.6.3.2 FAIR Data

Moving K research from its present culture of small research studies and limited data sharing to one where data are collected with the anticipation that they will be reused in syntheses and modeling requires development and implementation of best practices that ensure readability over time and across an array of agronomic disciplines. In 2016, Wilkinson et al. articulated the basic principles of data sharing: data must be FAIR (findable, accessible, interoperable, and reusable). The principles emphasize consistent use of appropriate metadata, and machines must be able to assist in finding, obtaining, and subsequently reusing relevant data. In the absence of metadata, natural language processing can be used to search for relevant data resources that are inconsistently described (Joseph et al. 2016). Application programming interfaces can be written to convert dissimilarly structured data into a uniform structure for integration, provided the data are annotated sufficiently for a secondary user to understand. Moving toward common metadata and data standards will accelerate data reuse, and agricultural standards are under active development as are tools to facilitate FAIR data workflows.

Tools include workflows for consistent use of data and metadata standards, controlled vocabularies, and agricultural ontologies (Brouder et al. 2019). Baker et al. (2016) have described a global multilingual concept scheme, an attempt to combine the most useful terms from three broadly used sources. An ontology is an organized, typically hierarchical, set of concepts and categories with explicit properties and interrelationships. Ontology terms have uniform resource identifiers and, when used appropriately, contribute to interoperability. Aubert et al. (2017) used

several existing ontologies, agronomic expertise, and the data standards from the International Consortium for Agricultural Systems Applications (White et al. 2013) to build an Agronomy Ontology (AgrO). AgrO describes agronomic practices, techniques, and variables used in agronomic experiments; associated field and desktop tools permit real-time development of FAIR data during experimentation as well as rectification of existing data into FAIR formats. Finally, because practitioners often use different terminologies than the scientists doing the research to inform practice, Ingram and Gaskell (2019) have proposed a methodology for co-production of ontologies with disparate stakeholders to make smarter search engines for agriculture.

1.6.3.3 Repositories and Data Publications, Catalogues, Registries, Knowledgebases

Potassium research will likely continue to be pursued by individuals or small teams of researchers dispersed across the globe, but an array of e-infrastructures is emerging to support a more data-driven, integrated approach to K recommendations. An ecosystem of repositories is emerging with the intent to foster FAIR data. General-purpose publishing repositories (e.g., Dryad [2020]) and institutional repositories (e.g., P.U.R.R n.d.) are non-specific, but they can ensure that data are appropriately annotated with metadata and exposed to relevant search engines. Potassium data are beginning to populate these resources. For example, Berg et al. (2020) published an 8-year study focused on the impact of P and K nutrition in alfalfa yield, quality, and persistence. These data are fully open access, have been downloaded to date over 600 times annually, and can be accessed, downloaded, reanalyzed, and formally cited when used in a novel analysis.

Some repositories can publish data as publications and assign a digital object identifier (DOI) ensuring their persistence in the scholarly record. Van Tuyl and Whitmire (2016) consider standalone data publications that follow citation conventions to be essential for incentivizing data preparation and ensuring wide accessibility. Several major repositories also offer data catalogues and registries. Catalogues facilitate locating similar datasets whose location is dispersed. Registries can expose metadata and content summaries to search engines but typically require additional steps to gain access to the data, thereby allowing concerns about privacy needs and embargoing to be addressed. Another form of registration could directly incentivize researchers to follow through with preparing all data for reuse and publication irrespective of outcomes. Advocates for improved reproducibility in science propose registering projects with a funding organization or a peer-reviewed journal prior to data collection as a way to prevent negative, null, and replicative results from being relegated to the grey literature (Nosek and Lakens 2014; Kupferschmidt 2018).

Finally, with sufficient investment and careful consideration for sustainability, the creation of a K knowledgebase would be a robust and innovative way to foster collaboration among researchers and advance K cycle science. As described by Gabella et al. (2017), knowledgebases are “organized and dynamic collections of

information about a particular subject” and differ from repositories in that multiple data sources are not just archived but curated for a purpose with review, distillation, and manual annotation by experts. A K knowledgebase could create the consistent and reliable source of scientific knowledge to effectively deliver to practitioners credible, salient, and legitimate scientific information. Identifying space for K research activities within general agronomic knowledgebases such as the Ag Data Commons (USDA-NAL [n.d.](#)) or GARDIAN (CGIAR Platform for Big Data in Agriculture [n.d.](#)) would be an efficient way to leverage investments in data tools that would otherwise be well beyond the resources currently allocated to agronomic K research.

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